DESIGN AND DEVELOPMENT OF AN EXTENDED RANGE ELECTRIC BY-WIRE/WIRELESS HYBRID VEHICLE WITH A NEAR WHEEL MOTOR DRIVETRAIN

by

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ABSTRACT

With automobile propulsion energy sources turning away from petroleum, the evolution of technology naturally lends itself to electrical hybrid vehicle architectures relying on alternatives as a primary electrical energy source. This thesis presents a design solution of a direct-drive and drive-by-wire prototype of a hybrid extended range electric vehicle (EREV) based on a dune buggy test bed. The developed setup eliminates nearly all mechanical inefficiencies in the rear wheel drive transaxle drivetrain. All controls have been purposely designed as a duplicate set to allow for full independent control of both rear wheels in a truly independent architecture. Along with the controls supporting the design, the motors have been mounted in a near wheel fashion to adequately replace a true hub motor setup. In addition, by-wire throttle and by-wireless brakes in a servo-mechanical fashion have been developed. The by-wireless braking system is used to control regenerative braking for the rear of the vehicle only allowing for the front brakes to be the primary means of braking as well as a mechanical safety redundancy. This design allows for developments in the areas of truly independent electronic differential systems and studies of the effect of near wheel motor setup. The efficiencies gained by the design solutions implemented in this thesis project have shown their ability to be used in a functioning motor vehicle. Direct gains in mechanical efficiency as well as the removal of a non eco-friendly gasoline powertrain have been attained. In addition, an electric architecture has been developed for further research in future studies such as vehicle stability control, traction control and all-wheel-drive architectures.

Dedication

I would like to dedicate the hard work and persistence that was performed in this thesis to my Mother Anna Bernacki for her determination in motivating me to continue my education and constant push to allow me to advance myself.

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List of Abbreviations, Symbols, Nomenclature

Symbols

δ	Ackerman angle
δ_{in}	Angle of inner tire
δ_{out}	Angle of outer tire
ω_{in}	angular speed inner wheel
ω_{out}	angular speed outer wheel
L	length
R	Outer radius
r	Inner radius
Φ	Flux
I_a	armature current
v_{diff}	velocity at the differential
V	Voltage
v_a	armature voltage
R_a	armature resistance
t	time (S)
V	Linear speed
K	Fixed Motor Constant
B	Flux density, lines/in^2
H	Magnet Field Strength
u	Resistance to magnetizing force

Abbreviations

EREV	Extended Range Electric Vehicle
FbW	Fly-by-Wire
BFS	Backup Flight System
PASS	Primary Avionics Software System
DbW	Drive-by-Wire
SbW	Steer-by-Wire
BbW	Brake-by-wire
BbWs	Brake-by-Wireless
ICE	Internal Combustion Engine
CV-Shaft	Constant Velocity Shaft
PCM	Powertrain Control Module
ECU	Engine Control Unit
BCM	Body Control Module
CANBUS	Controller Area Network
DPS	Data Processing System
GPC	General Purpose Computer
TC	Traction Control
BA	Brake Assistance
EHB	Electro-Hydraulic Braking
EMB	Electro-Mechanical Braking
ACC	Autonomous Cruise Control
ASR	Anti-Slip Regulation
FMEA	Failure Mode Effect Analysis
FR	Function Requirement
DP	Design Parameter
HofQ	House of Quality
QFD	Quality Functional Deployment

Chapter 1 Introduction

1.1. Preamble

With the automobile industry cautiously turning away from petroleum and towards electrical energy as a primary source of automotive propulsion power, the evolution of automotive powertrain design and technology naturally lends itself to having an electrical control system rather than a mechanical one. Electrical control systems offer advantages in safety, user control and efficiency.

1.2. Introduction

In this context, the conversion of GM's Pontiac Solstice into an electric hybrid vehicle has been envisioned as a motivating long-term research objective of this thesis. Among the other comprehensive and extensive undertakings necessary to accomplish this goal, two major tasks have been selected to comprise the scope of this thesis. First, this includes the development of a truly independent drive system. Second, it includes replacing the mechanical control system with a by-wire system.

The primary goal of this thesis is to provide the scientific and engineering fundamentals for the design, development and analysis of truly independent electrical drive automotive systems and by-wire technologies that will be developed and implemented within the scope of the thesis. The thesis will discuss their state of the art, advantages and disadvantages, and ultimately propose viable solutions intended for the Pontiac Solstice to be retrofitted as a drive-by-wire electric hybrid vehicle while testing these solutions on a dune buggy based architecture test bed. Besides fulfilling the primary goals of this thesis, as a common practice in developing vehicles, passenger safety and comfort will be closely considered throughout the entire exercise.

1.3. Current State of the Art

Originally implemented into bicycles as a compact form of propulsion, hub motors have not yet reached the major OEM market in automobiles. This truly independent system stems from the principle of encompassing a motor into the hub of a wheel and using it to propel a vehicle. The everyday bicycle was transformed using permanent magnet motors in the shape of a thin disc mounted on the main axel of the rear wheel. The purpose of the motor would be to substitute the pedalling action allowing the operator to rest or to assist during difficult manoeuvres such as steep grades. The advantages in bicycles were easily seen, with space constraints being the main design parameter the motor was not able to be mounted exterior of the thinly profiled bicycle frame. The hub motor worked as an ideal solution and performed well for the small size of a personal bicycle. However, hub motors carry on this movement towards further improvements in efficiency and safety [1].

The current state-of-the-art in hub motors includes the efficiency advantages of a direct drive setup and the ability to have full independent control of all driven wheels. Thereby, the extents to which hub motors can be implemented into vehicles electronics are virtually endless. Weight savings can be seen by the removal of heavy components such as transmissions, transaxles, differentials and associated power transfer mechanics. The weight savings can be seen as direct efficiency gains as long as the hub motor setup carries strict constraints in overall mass of the assembly. In addition, the sheer weight savings found in a by-wire vehicle milieu is an additional benefit in the realm of overall vehicle efficiency. By removing hydraulic systems and mechanical linkages in order to replace them with low mass wiring the power to weight ratios in vehicles can be drastically improved [2].

The shift from mechanical linkages and connections to electrical by-wire technologies has gradually occurred in modern day aircraft over the past 50 years in order to improve safety and performance usability. Multitudes of successes in such advanced aircrafts have been related to the F16 fighter and the otherwise inherently unstable F-117 stealth fighter [3]. However, the automotive industry is currently making its first steps towards adopting this technology. Safety will always be the number one priority when developing and designing future vehicles. On the other hand, customer comfort as well as control customization and better ergonomics are continuing to play an integral role in influencing new vehicle sales.

The current state-of-the-art in by-wire technology advantageously allows for advanced computer control of various user inputs such as acceleration, braking and steering in emergency situations. Systems such as traction control, stability control and advanced assisted braking can all be integrated to work together to perform as one system. This system can be made to offer responsiveness that a human driver could otherwise not provided [4]. In addition to crash avoidance systems, design of the overall collapsible chassis and structure of a vehicle is equally important, in the event that a collision is unavoidable. By implementing “steer by wire” systems, vehicle designers are able to remove elements that could cause severe damage to occupants, elements such as the steering column that in the incident of a frontal crash would be driven into the cabin possibly causing fatal injuries [5].

The current state-of-the-art in controls in vehicles has reached a new level of precision and customization. By-wire technologies allow vehicles to advance to a whole new generation of in-vehicle control systems. The user can have 100% control on settings that control the feel and over all responsiveness of user inputs. Steering can be made to be as responsive as a race car or instantly converted to that of a luxury sedan. The same can be performed with the feel of the brakes, throttle and even transmission shifts. All can be instantly programmed and customized to the user's specification and fine tuned thereafter. A crucial element of any new technology is efficient design. Efficiency in a by-wire technological environment can be obtained by modifying shift points controlled via a by-wire transmission, or by limiting and optimizing throttle positions. More advanced driving algorithms can be incorporated due to the interaction with powerful computer controllers now found in vehicles [6].

1.4. Overview on Fly-by-Wire (FbW) Controls

The automotive consumer indirectly drives the improvement of the vehicle market by constantly demanding faster and more efficient cars, all while having them become more reliable, durable, and safer. This demand can be met by continuing to adopt technologies from the demanding aerospace world to exceed the expectations of the automotive world.

Aerospace technologies have been adopted into automobiles since the early inception of the passenger vehicle. Attributes such as aerodynamics, selection of engineered materials, performance characteristics, guidance and occupant safety all have been influenced by existing aerospace technologies. With the onset of automobiles becoming more and more dependant with electronics and computer foundations it is a natural step for further development in wired controls to be evident in vehicular designs [7].

With the demands expected in aircraft technology being far greater than those expected from automobiles there is no surprise to see technologies embraced by the automotive world stemming from aircrafts. These expectations stem from the fact that airplanes subsistence depends on the technologies that enable them to fly. Comparisons such as the effects of a stalled engine on a plane would be much more severe when compared to the same scenario in a vehicle. A plane could plummet from the sky, where as a vehicle would coast to a stop. Similar scenarios such as efficiency and ability to overcome distance; a plane if not efficient enough may not be able to span an open ocean, where as a vehicle would be stuck on the side of the road. In extreme scenarios performance plays an ultimate factor in fighter jets; where performance of a plane may enable it to manoeuvre through a danger zone through various altitudes and high speeds, where a vehicles performance would allow it to pass an adjacent vehicle or in a trivial manner win a race.

Fly-by-wire (FbW) technology is defined as a flight control system that uses electric wiring instead of mechanical or hydraulic linkages to control the actuators for the ailerons, flaps, and other control surfaces of an aircraft. By-wire technology was first used in airplanes in the early 1950's, when it was exploited by the military. Military jets such as the 1953 Avro Vulcan (Figure 1.1) incorporated analog fly-by-wire control systems into its flight controls [8].


Figure 1.1 - 1953 Avro Vulcan [9]

Mechanical servo valves were replaced with electrically controlled servo valves controlled via an analog computer controller. These first steps in the aerospace industry paved the way for the mainstream of by-wire technology in fighter jets and airplanes. The extremely popular Avro Arrow in 1958 exchanged the analog computer controller with an electronic controller [10].


Figure 1.2 - 1958 Avro Arrow [10]

This supersonic plane that was controversially cancelled, was at the pinnacle of technology when it was introduced, which was fitting that it came equipped with the latest of by-wire technology. Even the most famous fighter jets such as the F16 Fighter (Figure 1.3) in the late 1970's exhibited by-wire technologies. By-wire technology enabled these prized fighter jets to display unprecedented maneuverability due to the ability of the analog controller to compensate the inherent negative stability of the aircraft a trait which trades stable flight for increased maneuverability. By-wire technology in this case will allow the aircraft to display relaxed stability; the aircraft will oscillate in a simple harmonic motion around a set attitude while decreasing amplitude [11].

Figure 1.3 - F16 Fighter Jet [12]

The sudden increase of by-wire technologies allowed for far more advanced aircrafts to be released, such aircrafts such as the Lockheed Martin F-117 Nighthawk (Figure 1.4) which was virtually impossible to fly by human hands until a sophisticated by-wire control system was implemented to control the inherently unstable aircraft. The systems used in aircraft have to be totally redundant with no chance of failure [13].

Figure 1.4 – 1977 - Lockheed Martin F-117 Nighthawk [13]

The F-117 incorporates a quadruple redundant flight control system through its by-wire system which was initially developed in the F16. In the same year the F-117 Nighthawk was released (1977) the US space shuttle program (Figure 1.5) instituted digital fly-by-wire controls which were first used in free-flight approach and landing tests. The shuttle used five identical redundant IBM 32-bit model AP-101, general purpose computers (GPCs). These five computers were programmed with system software called the Primary Avionics Software System (PASS).

Figure 1.5 – 1977 U.S. Space Shuttle Program [13]

A fifth backup computer runs separate software called the Backup Flight System (BFS). Collectively they are called the Data Processing System (DPS). The purpose of the five systems is so the shuttle can have one failure and still be able to run flawlessly, it can have two failures and still be able to land without issue. The decision making ability of the systems allows the properly functioning computers to rule out the failed computer and render it out of service. This type of redundant failure control is crucial when dealing with sophisticated systems and allows by-wire systems to be an exceptional alternative over traditional mechanical connections [14].

In the early 1980's the trend to use by-wire controls in aircraft continued. The first commercial airliner to fully utilize by-wire digital control occurred. In 1984 the Airbus A320 (Figure 1.6) a medium range aircraft pioneered the use of by-wire controls in an aircraft that would transport civil passengers [15].

Figure 1.6 – 1984 Airbus A320 [15]

Although the A320 displayed advanced by-wire controls, via a digital processor, the processors at the time were the latest and greatest. The by-wire control system utilized the Intel 8086 architecture, a 16 bit process and one of the earliest processors released. By today's standards this processor is out performed by graphing calculators that exhibit more processing power then the 8086 [15].

Finally in 2005 the first business jet was released fully utilizing by-wire controls the Dassault Falcon 7X. All the flight control actuators and control laws were designed and built by Dassault [16].

Figure 1.7 - 2005 Business Jet - Dassault Falcon 7X [16]

The advanced capabilities of the by-wire controls on this aircraft allow it to make automatic trim adjustments during configuration changes, swap controls seamlessly between cockpits, calculate and exercise maximum aircraft performance such as maximum angle-of-attack and will also aid in emergency manoeuvres for collision avoidance or wind shear incidents. Additional luxurious features were made available due to by-wire technologies such as to adding the comfort of turbulence compensation to enable a softened ride for passengers [15][11].

1.4.1. Advantages of By-wire Systems in Aerospace

The advantages that by-wire controls bring to aircraft are substantial. The simple aspect of removing mechanical devices and complex linkages which have to be maintained in a preventative maintenance fashion can prevent unexpected failures from occurring. In addition, normally routed hydraulic circuits can be removed. This aids in the performance of the aircraft by reducing weight and it also eliminates the chance for a hydraulic failure such as a leak which could lead to a catastrophic calamity. From a manufacturing and design standpoint, by utilizing wire for point to point control, the routing of control wires becomes extremely accommodating, as wires are inherently flexible. Wires also offer the added benefit of being easy to protect by both shielding means and protective insulation. The removal of all connecting mechanical hardware such as hydraulic lines, hydraulic valves, and a majority of hydraulic fluid reservoirs, has a considerable weight savings, if the weight of mechanical linkages connecting point to point controls is added, the total weight conserved increases substantially. By reducing the weight of the aircraft, efficiency is increased, cargo by weight can be increased and agility can be enhanced [9].

With additional electronic subsystems by-wire controls can be enhanced further by automating control processes to allow for safety integration and convenience options. In the aerospace industry; military, commercial and business class aircrafts utilize such devices to perform a variety of tasks. Many of the already mentioned types of aircrafts have control features such as auto stabilization, whether to control the inherent instability of the plane like the F-117A or to improve the flight quality for passengers during turbulence such as in the Airbus A320. Navigation systems can be tied into by-wire controls for such well known features as auto-pilot where the no human assistance is needed in order to guide the plane to the desired destination. By severing the mechanical connection from controls to actuated devices, the transition to an auto-pilot configuration is increasingly simplified, since the computer controls can instantly take control of the actuators through a by-wire configuration. Again, the auto pilot system can utilize the already implemented redundancy of by-wire controls, with multiple computers checking for possible failures and passing on control to able controllers [15].

Military fighter jets utilize by-wire controls to integrate radar and weapons systems into the flight control systems. This allows for the weapon systems to compensate for speed and direction of the aircraft and provide the pilot with a reduced workload in an already high stress situation. Fly-by-wire controls coupled with state-of-the-art technology in target acquisition and tracking, integrated flight/fire control can increase firing opportunities, improve weapon accuracy and enhance survivability [17].

Another benefit that comes with electronic control is the ability to customize controller feel and response time from user to user. With electronic controls response can be near instantaneous with no lag or mechanical play in the system. This added responsiveness is important in such high performance demanding machines such as fighter jets, but also blends nicely in an autonomous control system for the lack of prediction needed in order to control delays caused by mechanical lag.

1.5. Implementing By-wire Controls in Automobiles

By analyzing the available technologies implemented over the past 50 years in the avionics field it can be distinguished that correlations occur between the controls of aircrafts and how they could relate to that of an automobile and in this case the Pontiac Solstice. The advantages that were described previously for aircrafts share many similarities to those in the automotive genre. The benefits stem from added control benefits perceived by the driver to added enhancements to efficiency, safety, performance and autonomy.

Drive-By-wire controls allow for many improvements in efficiency in an automobile, these efficiencies are gained by reducing weight, and allowing for the control of driving parameters through optimized computer algorithms. Weight reductions by implementing a drive-by-wire system into the Pontiac Solstice have many benefits. By removing such linkages as brake pedal arms, gas pedal arm and bowden cable forward weight can be reduced. As well hydraulic lines can be reduced as each wheel can be independently controlled via separated hydraulic systems. In the case of electromechanical braking hydraulic lines can be eliminated throughout the vehicles architecture. The weight reduced in the loss of hydraulic fluid although marginal still have an effect on a vehicles performance and efficiency. The loss of hydraulic fluid would have a positive effect on the environment however since harsh brake fluid would be conserved and fluid changes would be reduced. Any marginal gain towards weight reduction in today's competitive market is sought after to achieve the ultimate in efficiency in vehicles. For the Pontiac Solstice the weight reduction advantages are two-fold; being a performance enthusiast's vehicle the gains in acceleration are evident as well as gains in overall fuel economy efficiency is improved as well.

Overall efficiency of a vehicle can also be improved by such features as cruise control, where a subsystem takes control of the throttle to maintain a preset speed. This option allows for the optimal amount of throttle to maintain the speed preset by the user. Cruise control is not by any means a breakthrough technology as it has been around since the early 17th century on steam engines. However, although the basis of this technology is rather primitive more advanced forms of the system lend itself well to a by-wire control. Systems such as autonomous cruise control (ACC) utilize laser or radar to monitor vehicles ahead of the vehicle and pace the speed of the vehicle accordingly to traffic conditions. These electronically intelligent systems integrate well with an already electronic drive-by-wire control architecture. Efficiency in space utilization can also be had with by-wire control, with the loss of many mechanical linkages, or fluid transfer devices, space can be utilized more efficiently. Some brake by wire designs offers the elimination of all hydraulic lines and storage reservoirs. With steer-by-wire eliminating the steering shaft, column and gear reduction mechanism, some much needed engine compartment space is opened up [18].

Integration of safety features has become an increasingly important decision making factor in the selection of a vehicle for purchase. Such options as Anti-lock-brakes, airbags and seatbelts have become the standard in automotive safety features on all vehicles. With the addition of drive-by-wire controls additional features can be added and existing features can be greatly improved. Anti-Slip Regulation (ASR) can be controlled via a throttle-by-wire (TbW) control to actively monitor and adjust throttle position when the rear drive wheels (Solstice being rear wheel drive) spin faster than the front wheels. In this case, the rear wheels would be losing traction and the throttle would be closed accordingly to reduce engine power to the rear wheels. The term ‘throttle’ in this scenario is inherently linked with that of a internal combustion fuel injected vehicle, however the same theory can hold true for electric vehicles and by reducing engine speeds via an electric drive controller. No mechanical linkage, for example a Bowden cable, would need to be bypassed in order for this throttle modulation to occur, the same actuator that would normally activate/deactivate throttle positions would be used by the controller to achieve the most favourable throttle modulation. Another traction feature that can be used in conjunction with ASR is Traction Control (TC), the purpose of this system is to regulate the speed of opposite drive wheels by controlling individual braking to wheels which are spinning. The system usually used in conjunction with Antilock Braking System (ABS) monitors wheel speeds and will target the wheel spinning excessively and will pump the brake in a pulsating fashion to reduce the speed of the wheel to regain traction. Again, with by-wire braking this system can be controlled without the need to bypass any mechanical linkages controlling braking power. By-wire-braking also allows for a simple integration for Brake Assistance (BA) where braking power can be modulated by a computer controller to allow for proper braking conditions according to speed and direction. Brake assistance is able to apply braking to wheels that need it most and at the calculated force and duration, this type of braking is especially beneficial during corning conditions, or during high speed braking [18]. To allow the subsystems listed above to interact mechanically is a difficult task. However, by keeping the actuations mechanical and the controls electrical this task becomes entirely possible. By utilizing current automotive computer communication protocol such CAN BUS (Controller Area Network) the communication amongst several systems is possible. This would allow a drive-by-wire infrastructure the ultimate flexibility in both control and sensory feedback. Through this style of networking communication of several electronic control units (ECU) can occur. The placement of several ECU's can be made according to the specific items being controlled. This would allow for the brake control to be positioned near the brake electronics, the powertrain control module (PCM) can be placed near the engine or motor and the body control module (BCM) can be placed centrally within the chassis. This enables the various sensors and actuators that each controller is in command to interact through the bus network. This also allows such systems as brake assist, traction control, anti-slip regulation, anti-lock brakes to interact autonomously to offer such advanced features as stability control. With drive-by-wire technologies enabling such advanced communication amongst controllers and allowing control of actuators in charge of activating devices such as brakes, throttle and steering can result in a system that can react much faster than any human driver.

The addition of drive-by-wire control also allows for real-time monitoring to occur. With all inputs from the driver being processed through controllers and analyzed and compared to outputs performed anomalies can be detected and failures alerted to the user. Each individual control which is networked can have the ability to data-log and record in real-time positions of actuators in correspondence to driver input. Driver habits then can be monitored and recommendations for service can be calculated more accurately. In conjunction with an option such as Onstar ™ which allows for full satellite communication from the vehicle to General Motors will allow for even further feedback total vehicle diagnosis. The ability to send real time logged parameters via satellite communication, the information can then be analyzed and service can be scheduled for the vehicle and communicated back to the driver. This would allow such maintenance items such as brake changes, oil changes and filter changes to be scheduled as per the driving habits of the specific user, and each individual vehicle could be more accurately serviced depending on the exact needs of the vehicle being monitored.

Drive-by-Wire controls also offer flexibilities in manufacturing. With no mechanical linkages to route, or for hardened hydraulic lines to handle, the assembly of a by-wire vehicle becomes considerably less complex. A steering system commonly consists of a rack which contains tie rod ends that connect to steering arms. A pinion which moves along the rack is attached to the steering column or shaft. This shaft passes from inside the engine compartment through the firewall of a vehicle and into the cockpit of the vehicle. Within the vehicle the steering wheel is attached to this steering shaft. By eliminating the mechanical linkage from the steering wheel to the rack, installation becomes a much simpler process and can be installed as a modular unit. Eliminating complicated steps such as this reduces assembly costs and also reduces the amount of non-ergonomic operations on the assembly line such as routing awkward hydraulic lines overhead, mounting heavy steering columns form within the vehicle, and feeding hard to work with throttle cables through the firewall.

1.6. Implementing Hub-Motor Drivetrains in Automobiles

On many of today's hybrid electric vehicles (HEV) the power train is configured in a parallel configuration, where the electric motor is commonly a polyphase (3 phase) AC induction motor. The electric motor is coupled with a complex transmission that allows for the electric motor and secondary power train, usually a petroleum engine to propel the vehicle [19].

The losses in any vehicle with a transaxle transferring power from the motor to the wheels become a substantial part of the equation when calculating overall losses. The efficiencies of the transaxles have been calculated to be as much as 91% overall on a front drive helical gear transaxle. For rear drive configurations efficiencies drop as low as 82-85% due to the rear differential and driveshaft configuration [20].

1.7. Thesis Purpose

The purpose of the research conducted in the area of powertrain development and electrical architectures, including by-wire and by-wireless systems, presented in this thesis is to increase the efficiency, maximize manufacturing flexibility, minimize design rigidity and contribute to the overall safety of electric vehicles. Further motivation is provided by increasing the space constraints of current automobiles through orienting the powertrain to the outer corners of the vehicle as well as eliminating mechanical components developed to transfer the power from conventional powertrain devices to the wheels. Furthermore this thesis will be performed concurrently with another research project involving extended range electric vehicles. This research was conducted by a colleague Matt Van Wierengen and is entitled "Design and Development of a Custom Dual Fuel (Hydrogen + Gasoline) Power System for an Extended Range Electric Vehicle Architecture" [21].

1.8. Thesis Objective and Goals

The objective of this thesis is to produce a platform for a powertrain system to simulate and/or replace a hub motor drive setup. As a compliment to an electric hub motor setup, the project will explore by-wire and by-wireless technologies in regards to throttle and brake control. Research and development of these technologies will require a test bed vehicle. This will also comprise of an electric vehicle basis that will not only support the above mentioned technologies, but it will also be developed and tested in conjunction with the test bed vehicle. The test bed in its initial concept will be a commercially available baja style dune buggy (Figure 1.8) that will be purchased and is powered by a 250cc single cylinder carbureted engine (Table 1.1).

The test bed vehicle will need to undergo a complete architecture change from a rear drive, rear engine based gasoline architecture with a continuously variable transmission (CVT) to a series hybrid based electric vehicle or extended range electric vehicle (EREV). Combining the efforts of the design team, the final outcome will be a driveable hybrid vehicle that will include drive by wireless brakes, drive by wire throttle and a near wheel motor solution that will simulate that of a hub motor setup.

Figure 1.8 – Baja Dune Buggy Test Bed

Table 1.1 - Test Vehicle Original Specifications

Engine/Transmission	
Displacement [cc]	250 [cc]
Transmission	Auto – CVT
Engine Type	Single Cyl., 4-stroke, Water Cooled
Power (Max)	10.5 [kW]/7000 [rpm]
Torque (Max)	17.6 [Nm]/5500 [rpm]
Drivetrain	Shaft Drive, Rear Differential
Speed (Max)	80 [km/h]
Dry Vehicle Weight	385 [kg]

Chapter 2 Theoretical Background

2.1. Components

There are four major components that comprise a fully developed applied drive-by-wire system in a vehicle. These include the following:

- Steer-by-Wire (SbW),
- Brake-by-Wire (BbW),
- Throttle-by-Wire (TbW) and
- Shift-by-Wire,

All of the above components have a common feature with all by-wire technologies: they eliminate the mechanical linkage that connects a users command to the action represented by the command. This mechanical linkage is replaced with a 'wire' and a controller; an electrical actuator is at the end of the circuit performing the mechanical movement [16].

A hub motor setup incorporates an electric motor into the actual wheel assembly of the vehicle's tire assembly. Hub motors are currently commonly seen on pedal style electric bicycles and are an architecture that fits a compact densely powered motor into the form factor of a vehicles wheel. Hub motors have not reached the mass production stage in the automobile stage and have been very limited in the prototype stage with many accusations of false promises. Product details have been released without a real world prototype to back up the findings. Various hub motor prototypes will be discussed as well as claims on power and suitability for fitting of the hub motor into a vehicles tire assembly.

With each component having various degrees of variances in the technologies that represent them, this survey will explore the technologies that could be feasibly used within the Pontiac Solstice and comment on their advantages and disadvantages.

2.2. Steer by Wire (SbW)

The Pontiac solstice has a performance inspired rack-and-pinion steering system, with a ratio of 16:4:1 which translates into deft steering that aligns steering-wheel movement in direct linear response to the wheels [22].

The purpose of this configuration is to allow the driver to feel a direct connection to the road. Engineers have kept the system mechanical to allow for a constant and direct feedback from the load, so a driver could react and predict to current driving and road conditions. The challenge now is to take the characteristic feel of drivers direct connection to the road via mechanical means, sever it, and simulate it via electronics in order not to lose any of the feel of the performance inspired roadster. Advantages of adding by-wire steering has been discussed in Section 1.5, however it seems that by adding steer-by-wire the feel will be lost. Fortunately, due to the advancements in force feedback control this feel will not be lost but could actually be enhanced and customized to the user's preference.

Steering control via electrical means must have extreme precision. The radius of turning a vehicle should hold a nominal tolerance of less than one centimetre. To attain these tolerances is a must when designing any type of steering system, as well components must be sufficiently robust, reliable and fault tolerant as to not cause the possibility of a steering failure. Components include various sensors to monitor rotation angle, torque of the steering wheel and torque of the front tires [18].

2.2.1. Electromechanical - SbW

There are two setup options for steer-by-wire control and many derivatives of the two options. One of the two options is an electro-mechanical steering setup. The other option for steer-by-wire technology is completely independent electronic actuation. With the former setup a motor is positioned in place of the steering shaft, mounted to the pinion itself. The motor then has control of rack position and therefore can steer the vehicle via a controller. The controller being fed by inputs from a rotary encoder is in the form of a steering wheel or an axial joystick.

SKF displayed a rack-pinion style of Steer-by-wire setup in the prototype branded the Bertone SKF Filo (Figure 2.1).

Figure 2.1 Bertone SKF Filo Concept [19]

This prototype offered a rectangular shaped steering wheel, utilizing a turning motion similar to that of aircraft controls (Figure 2.2).

Figure 2.2 - SKF Steer-by-Wire Control for Bertone Filo Prototype [19]

SKF also addressed the issue of drivers' feel of the road, teaming up with Filo an active feedback system was created through the drivers control called the Guida. Within the yokes of the steering a high-torque motor is positioned to allow for programmed resistance to occur to allow the driver a sense of feel for the road. This allows the driver to have the tactile feedback on steering angle as well as overall road conditions [19].

2.2.2. Fully Electronic 2/4 Wheel Steering

In completely independent electronic actuation steer-by-wire technology, each wheel would have its own axially placed motor to enable it to pivot along the struts axis. The advantage of such a system is the ultimate of flexibility in steering control. Front and Rear wheels can turn independently of each other as well as being independent of any mechanical linkage from the input control.

This technology was demonstrated by Delphi in their Quadrasteer (Figure 2.3) system which was available in the GMT-800 General Motors full-sized pickups. Although the rear wheels were linked through a rack/pinion style setup, it did allow for true four wheel steering to occur [23].

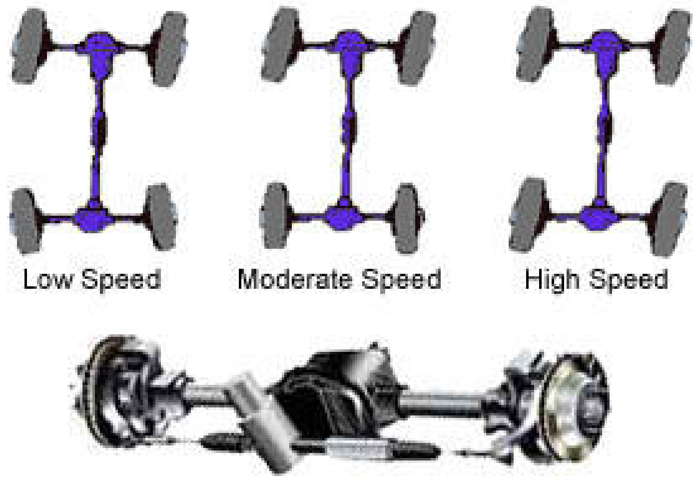


Figure 2.3 - Delphi's Quadrasteer - Rear Wheel Steering [23]

In the case of the Pontiac Solstice this would translate to an extremely tight turning radius unseen in any other performance car, as well as controlled nimble response during high-speed steering such as on highway lane mergers. Traditionally, such systems have been reserved for towing to allow people towing boats or trailers to be able to manoeuvre in tight quarters. In slow speed turning the rear wheels would turn opposite of the front allowing for a very tight radius to be followed.

2.3. Brake-by-Wire (BbW)

Brake-by-wire systems remove the mechanical linkage from the brake pedal to the actuator activating the brakes. As well, systems are available that will eliminate the hydraulic lines throughout the vehicle. There are primarily two types of brake-by-wire systems available; an electrohydraulic braking (EHB) system where the command from the driver actuates a linear actuator attached to the master cylinder. This replaces the linkage and entire assembly that goes from the brake pedal to the master cylinder.

The second system is an electromechanical braking (EMB) system. This system has individually controlled brake actuators on each hub assembly, and is a completely dry system with no hydraulic fluid, reservoir or distribution. Both systems offer the advantage of being easily connected with 'smart' systems such as traction control, anti-lock brakes and stability control. They also both offer the advantage of removing the large vacuum booster found on conventional hydraulic brake systems. (Figure 2.4) [24].

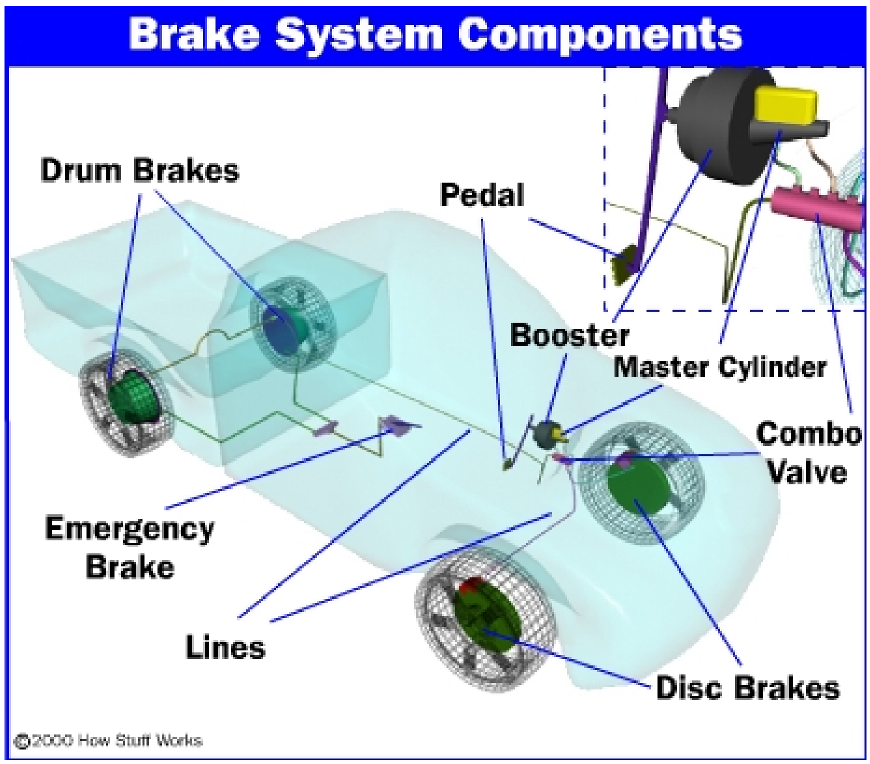


Figure 2.4 - Mechanically Actuated Conventional Braking System [24]

2.3.1. Electrohydraulic – BbW

Electrohydraulic braking offers the advantage of being easily adaptable into existing systems. The reason for this is the fact that the majority of the system remains the same and the only change being necessary is of the linkage from the vacuum booster to the master cylinder. With electrohydraulic braking a linear actuator is attached to the primary piston on the master cylinder (Figure 2.5).

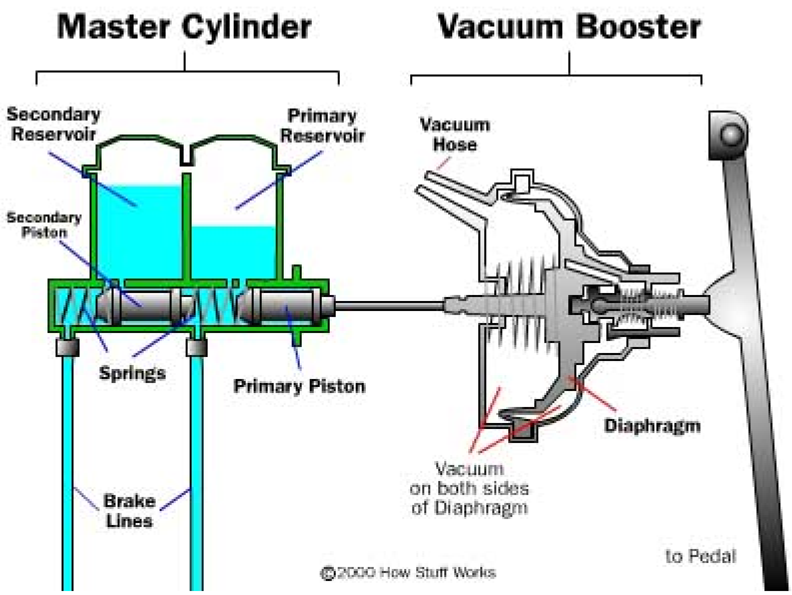


Figure 2.5 - Primary Piston on Master Cylinder Mechanical Connection [24]

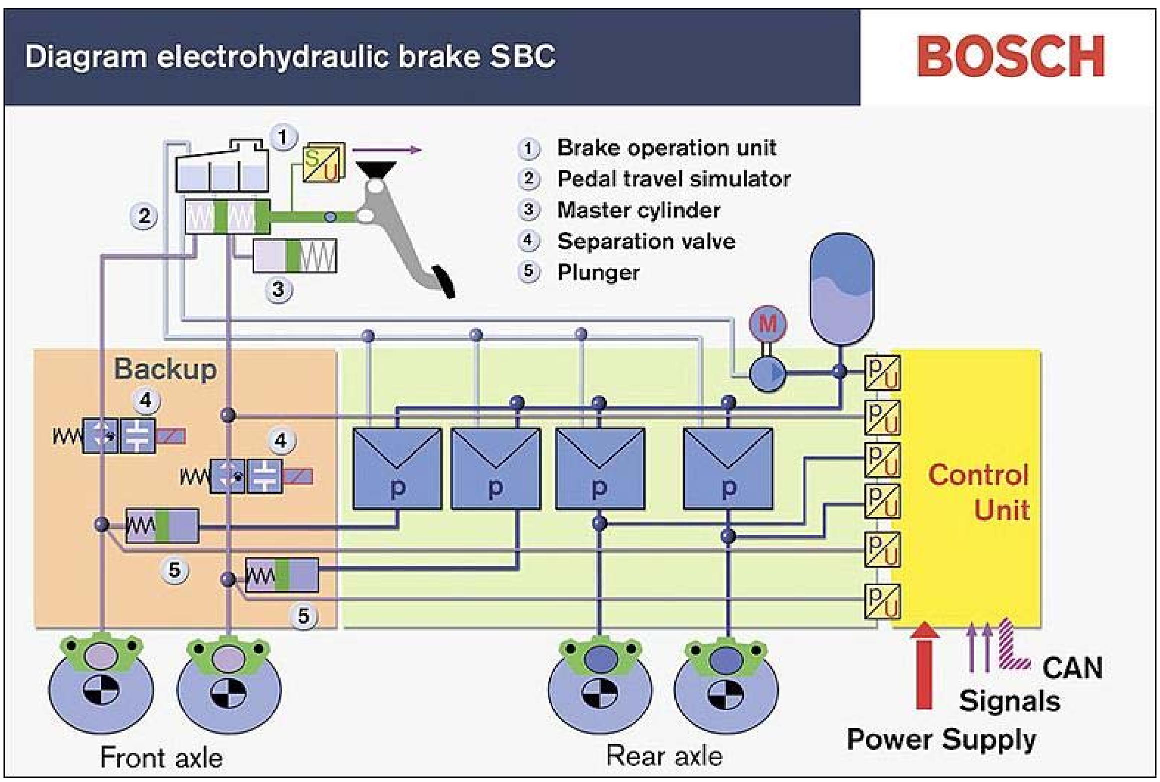


Figure 2.6 - Bosch Electrohydraulic Braking System [25]

When the brakes are actuated by the driver, the controller activates the linear actuator which then primes the master cylinder to actuate the brakes as they normally would be with the mechanical connection. Existing hardware such as anti-lock brakes which is an available option on the Pontiac Solstice can still be utilized together with electrohydraulic braking.

Bosch, a leading manufacturer of automotive components, has developed a suitable mass producible electrohydraulic braking system which initially was meant for a 42 volt architecture to be introduced into vehicles. With the advent of pure electric vehicles and the possibility of converting the Pontiac Solstice to pure electric or hybrid electric, the addition of a Bosch system seems plausible. The Bosch electrohydraulic Sensotronic Brake Control (SBC) system (Figure 2.6) has a common brake pedal that interacts with the driver, whereas the actuator pedal is connected to a series of travel sensors and pressure sensors that monitor how fast and with what force the brake pedal is actuated. This information is communicated to the control unit for processing which then commands the appropriate wheel pressure modulators. With the pedal connected to the travel sensors the pedal feel of conventional style brakes still remains, despite not being directly connected to the master cylinder. Bosch has also made gains in system efficiency and offers a 14 volt system that is currently found in the SL series Mercedes Benz class of vehicles. The system allows for a high degree of braking customization, from pre-programming moderate stopping power for the perfect chauffeur like stop, to intervening upon emergency braking via an electronic stability program (ESP) [25].

The brakes also have features such as the 'dry brake function' which chatter the brakes on and off to dislodge water and debris during rain/snow storms to ensure proper braking during harsh weather conditions. This system is activated with the windshield wipers are set in motion. Also, algorithms are in place to eliminate roll-back when a car is stopped on a high degree incline, braking resumes automatically after the driver's foot transfers from the accelerator pedal to the brake pedal, a feature called 'drive away assistant'. Features such as these were implemented primarily for larger luxury cars such as the Mercedes SL class, although useful in a car such as the Pontiac Solstice the cars genre does not suit the need for such high end comfort features.

2.3.2. Electromechanical – BbW

The alternative to electrohydraulic brakes is the electromechanical braking system. This system utilizes no hydraulic fluid, lines or reservoirs. This is a more sophisticated form of braking that has not seen the mass production world yet. The idea behind electromechanical braking is to have each wheel independently controlled by its own electrical actuator while keeping the system completely dry of fluids. Over and above electrohydraulic braking, electromechanical braking offers the elimination of hydraulic fluid, lines and reservoirs. This brings a significant weight savings that can be spread through the entire vehicle [26]. In addition, without the need for hydraulic fluid, maintenance on such fluids is unnecessary. Without the maintenance of hydraulic brake fluid, pollutant and environmental concerns have been met by eliminating the corrosive and toxic brake fluid. This system can also offer programmable options such as anti-rollback or 'hill hold' to prevent roll back while on steep grades. The system in its general form consists of a DC servo motor which is connected to a spindle which gives the braking pressure. The entire system is housed in a calliper similar to the hydraulic brake callipers seen in vehicles today (see Figure 2.7) [18]

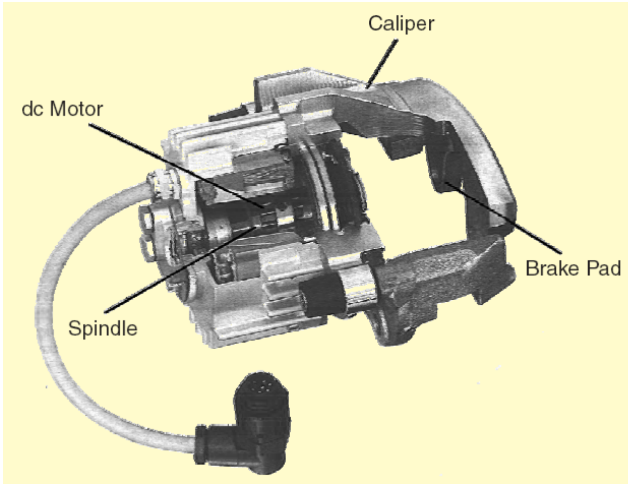


Figure 2.7 - Electromechanically activated brake assembly [18]

Siemens VDO offers an electromechanical brake system that uses a unique actuating mechanism. By utilizing an electric motor to press a wedge against the braking surface of a brake disc (Figure 2.8). Siemens VDO was able to create an innovative solution to the brake-by-wire design [27].

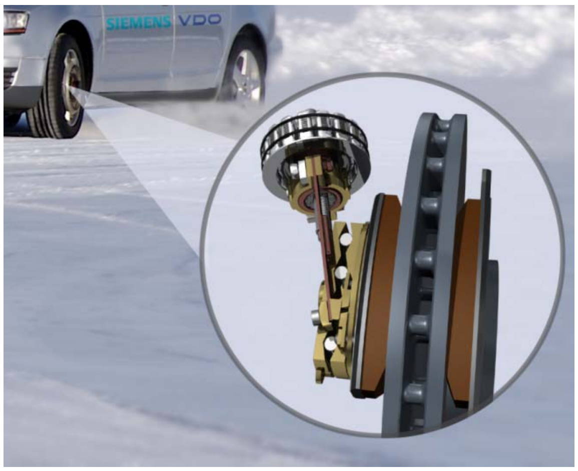


Figure 2.8 - Siemens VDO Electromechanical Wedge Braking System [27]

By taking advantage of the wedge principle's self-reinforcing affect Siemens VDO was able to produce tremendous braking power by displacing very little energy. A direct swap on a large sedan produced dramatic 15% increases in stopping distance during cold and wet conditions [27].

Newtech, a Canadian company, has also released a revolutionary style brake-by-wire solution. Instead of creating a caliper based surface to apply braking pressure, Newtech decided to utilize the entire disc surface to apply pressure to. With the system surrounding the entire rotor 75% of the brake rotor is in contact with the pad surface at one time. With pressure being applied from the inner pad disc, the floating rotor gets sandwiched between the inner and outer pad layers. This style of braking system has been commonly seen on industrial cranes, stamping presses and on some sports motorcycles but has never been implemented into automobiles. Newtech claims that their system is easily adaptable to a brake-by-wire solution, and has bid on contracts to build their full contact brake system coupled with a by-wire system for Renault and for the Saleen S7 super car [28].

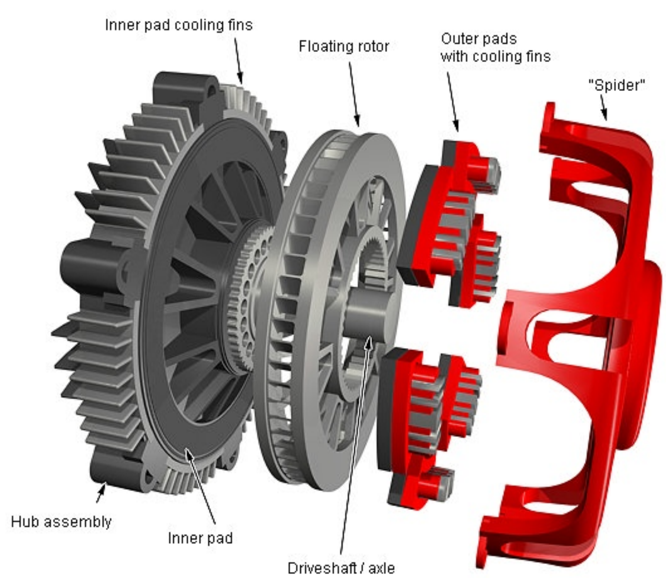


Figure 2.9 - Newtech Full Contact BbW [28]

By analyzing the claims that Newtech is making for their new braking technology, it is clear to see that this style of brake sole purpose is to stop a vehicle extremely fast. A car best suited for this style of braking would have to be a high powered sports car, and undoubtedly would be an over engineered solution for a smaller vehicle such as the Pontiac Solstice.

2.4. Throttle-by-Wire (TbW)

The most put into practice by-wire technology to date is Throttle-by-wire, also called Electronic-Throttle-Control (ETC). TbW has been used extensively used on many of today's vehicles from full size pickup trucks, high end luxury vehicles (Figure 2.10) to high performance vehicles such as the Corvette. The purpose of Throttle-by-wire is to remove the Bowden cable from connecting your gas pedal to the throttle body of the vehicle [29].

Figure 2.10 – 2003 Corvette TbW Throttle body

The 2007 model year of Pontiac Solstice has been fitted with its own electronic throttle control pictured in Figure 2.11. Throttle-by-wire technologies although important in the larger drive by wire picture will not be researched in the scope of this thesis due to it being already implemented into the design of the Pontiac Solstice. The assumption will be made that the existing TbW control can be placed with minimal modification into older models without issue.

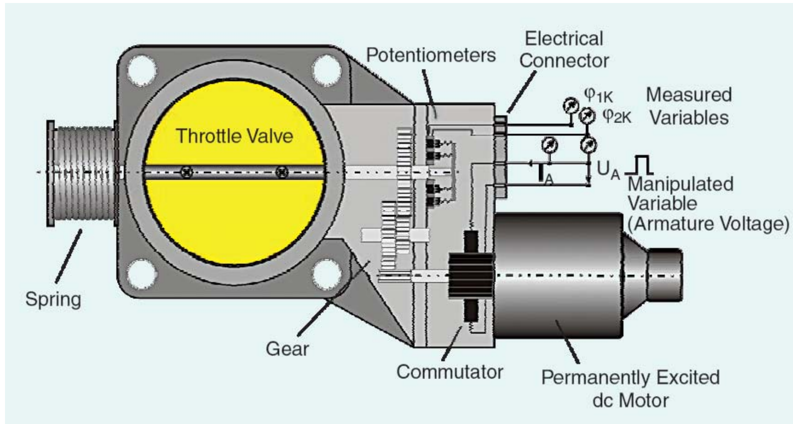


Figure 2.11 Schematic of TbW Control [18]

Pontiac states on their website advertisement: "Electronic Throttle Control (ETC) replaces throttle cable with electronics and algorithms for remarkably precise engine and vehicle response. Rpm-based versus speed-based, it tailors throttle behaviour to be more deliberate or unfettered as input demands" [22].

This general purpose is obviously related to that of an internal combustion powered vehicle which the Pontiac Solstice is in its OEM form. Throttle-by-wire is the preferred choice for electric vehicles; however no throttle body plate is controlled in this case. Signals to a motor speed controller need to be communicated through the bus network. A throttle-by-wire system is composed of a throttle pedal position sensor and a servomotor attached to the throttle plate. The throttle plate also has a potentiometer or throttle position sensor (TPS) mounted on it to monitor opened/closed percentage in volts. As the throttle is depressed, signals of throttle pedal position are sent to a controller which commands the servomotor to open the throttle butterfly as the pedal is depressed (Figure 2.12). Common redundancy is typically achieved via a servo motor electronic controller as well as a TPS sensor.

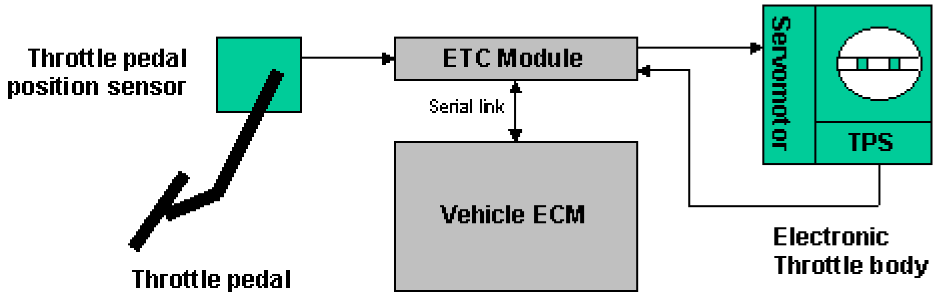


Figure 2.12 - Throttle-by-Wire Component Schematic [30]

Throttle-by-wire technologies have proven to be a reliable substitute to a Bowden cable design and offer many benefits from increased throttle response to manufacturability from the lack of feeding a long cable through the firewall. Features such as adaptive cruise control can also be programmed into the throttle controller with no need for extra hardware to enable such an option. Other features are also dependant on a throttle-by-wire system in order to get full functionality. Traction control and anti-slip regulation commonly use throttle-by-wire to interject on drivers controls to decrease engine speed to regain traction. In the case of most of today's production vehicles when a wheel over speed, loss of traction scenario occurs and throttle is cut back via the power train control module. The module will override the user's input signal from the throttle pedal, and command the throttle body's servomotor to close in order to bring engine speeds to a manageable level for traction to be regained. Similar programmed precautions are implemented to help eliminate possible damage to the engine. For instance, while in park many vehicles cannot be revved past a set RPM level, the computer overrides full throttle conditions and will only allow the throttle plate to open enough for a safe constant RPM (usually around 3000 [rpm]).

2.5. By-wireless Systems

The next step in progression from by-wire systems and the benefits associated by the electrification of the automobile is using more advanced forms of electrical communications such as wireless systems. The electrical communication that occurs wirelessly within an automobile to communicate controls, sensory feedback or accessory features is known as telematics. This form of communication is currently used by cell phones, smart phones, GSM devices, laptop computers as well as media playing devices. A wireless network can be used for in-vehicle communications and can be expanded to inter-vehicle communications such as vehicle-to-vehicle transmissions or vehicle to roadside smart highway applications [31].

Like by-wired technologies by-wireless systems are meant to increase efficiencies by removing components and allowing for the communications of control to be done electronically versus mechanically. Whereby wired technologies remove mechanical components and replace them with wires, by-wireless remove wires and replace them with senders and receivers. By-wireless technologies are able to greatly reduce the amount of wiring in a vehicle thus making the vehicle lighter, more cost effective, and easier to build. In addition, the efficiencies gained would directly affect fuel-efficiency which lends well with the movement towards electric power trains [32] [33].

Currently, technically advanced vehicles are equipped with a CAN-BUS architecture, which allows for multiple modules within the vehicle to communicate through wired communication bus channels. The increased electrification of the automobile will further complicate these networks and add to the current wiring already occupying a vehicle [33]. The wiring harnesses in today's vehicles are not only heavy and bulky, but they are complex and rigid in nature due to the cost effectiveness in creating wire bundles rather than individual strands. These harnesses are the bulkiest and most expensive electrical component in a vehicle and add up to 50 [kg] to a vehicle's total mass [34]. Wireless telematics can be used for many in-vehicle and inter vehicles technologies such as navigation and traffic systems, voice recognition and wireless internet connections, collision avoidance systems, crash notification, security systems and diagnostic and maintenance systems [31]. In order to implement a wireless communication Personal Area Network (PAN) into the OEM market of automobiles a standardized protocol will need to be introduced to minimize the effects of interference and transmission reception. Several wireless protocols have been developed or can be adapted to be utilized in automobiles. These wireless technologies are as follows:

1) Bluetooth
2) ZigBee
3) Ultra Wide Band (UWB)
4) Wi-Fi

These technologies will be analyzed on their suitability for real-time wireless control of vehicles. Such control systems include, by-wireless braking, by-wireless steering and by-wireless throttle, in which by-wireless braking will be explored in the experimental portion of this thesis. The wireless protocols listed will be required to transmit at relatively high speeds and allow for high bandwidths when interconnecting several vehicle networks [32]. The protocols should be standardized as all of the above (1-4) are. They should be able to transmit data throughout the entire vehicle with a transmission range of only a few metres (3-6 [m]). Power usage should be kept to a minimum as efficiency is key when designing an electrified vehicle. As well the protocol should be able to handle several devices and multiple communication events separately as well as concurrently as many events in a vehicle must be compared in real-time in order for logistics and fault-tolerance to be at a maximum. Finally, safety and redundancy should be a major focus in selecting a wireless protocol in which key components of the vehicle will be controlled by [31].

Bluetooth has been implemented into automobile technologies through the use of hands-free cell phones, which offered a low cost, short range ad hoc interconnection with the vehicles stereo system in order to transfer voice audio. It operates in the ideal range of 10 [m] making it perfect for even the largest of automobiles. It is a standardized wireless communication protocol under IEEE 802.15.1 and can work at current speeds of 3 [Mbps]. Bluetooth has also evolved quickly with the increasing needs of wireless technologies, moving from 1 [Mbps] in version 1.0 to 12 [Mbps] in upcoming version 2.0. This technology also offers a frequency hopping ability that enables it to be fault tolerant in harsh environments such as that in an automobile [31]. Currently Bluetooth has only explored the realms of accessory control in vehicles however many possibilities exist for this technology as wireless vehicle control systems are developed [32].

The next technology that is comparable to Bluetooth is ZigBee, which is also a standardized wireless protocol under IEEE 802.15.4. ZigBee is a low-cost and low power wireless PAN standard which is intended to communicate amongst sensory control devices. Over 120 company members (since 2004) have ratified and agreed upon the industry specifications that ZigBee now employs as its wireless standard, giving large promise to its use in industry. ZigBee however only operates up to speeds of 250[Kbps], which limits its bandwidth potential in high traffic, multifaceted vehicle networks [31].

One of the most common types of wireless networks found today is Wi-Fi or

IEEE 802.11a/b/g. These networks are used in wireless local area networks (WLAN) and can be found in homes to share internet or as a replacement to hard wired 100baseT networks. 802.11 standards have developed increased security protocols through Wired Equivalent Privacy (WEP) or Wi-Fi Protected Access (WPA), as well as the ability to address multiple components on the network. Speeds on Wi-Fi networks are extremely high ranging from 11 [Mbps] on 802.11b to upwards of 54 [Mbps] on 802.11a/g. 802.11b/g have an increased range at over 50 [m] which requires fewer access points in WLAN's however this is not a concern when used in a inter-vehicle solution. If developed for vehicle-to-vehicle communications range would be a factor, however for inter-vehicle control a range of under 10 [m] is needed. A draw back from this technology is that it consumes large amounts of power when compared to other technologies such as Bluetooth and ZigBee [31].

The last technology to be investigated is Ultra Wide Band (UWB) which is standardized under IEEE (802.15.3a) standards. Unlike the previous wireless protocols, UWB broadcasts at varying frequencies between 3.1-10.6 [Ghz] compared to 2.4Ghz/5 [Ghz] in technologies such as Bluetooth, ZigBee and Wi-Fi [33]. This broad frequency range allows it to be very tolerant to the interfering environments found in an automobile. UWB is able to transmit at very high bandwidths ranging from 50-100 [Mbps] and up to an impressive 480 [Mbps]. Performance of 50-100 [Mbps] can be expected in distances up to 20 [m] and faster speeds in short distances of under 10 [m] which makes this protocol very suitable for the relatively small distances spanning an automobile. Further advantages that UWB holds includes the facts that it is very cheap to build, it consumes very little power, and as previously mentioned operates at a varying frequency range.

When the aforementioned wireless technologies are explored it is clear to see that many share similar characteristics in frequency spectrum, range, and standardization through IEEE standards. However some traits set some technologies apart from others. Bluetooth offers the advantage of being highly utilized in the automobile industry currently, as well as having many OEM suppliers currently manufacturing units for low costs. ZigBee offers the advantage of being designed for sensor and control systems and its ratification with over 120 companies to mold its specification. Wi-Fi offers high transmission rates, and a commonality that is already seen in WLAN's across the world. Finally, UWB offers extremely fast transmission rates of over 100 [Mbps], is a low power solution, and operates at a distance and variable frequency perfectly suited for an inter-vehicle environment [31].

Table 2.1 Wireless Technologies for Automotive Application [31]

Standard	**Bluetooth**	**ZigBee**	**UWB**	**Wi-Fi**
IEEE #	802.15.1	802.15.4	802.15.3a	802.11 a/b/g
Freq. Band	2.4 [Ghz] @ 2.5 [Ghz] (ver 1.2)	2.4 [Ghz]	3.1 – 10.6 [Ghz]	2.4 [Ghz] (b/g) & 5 [Ghz] (a)
Network	P2P	Mesh	P2P	P2P
Modulation Technique	Frequency Hopping Spread Spectrum (FHSS)	Direct Sequence Spread Spectrum	Orthogonal Frequency Division Multiplexing (OFDM) or Direct Sequence UWB (DS-UWB)	OFDM or DSSS with Complementary Code Keying (CCK)
Maximum Network speed	1 [Mbps] (ver 1.0) 3 [Mbps] (ver 1.2) 12 [Mbps] (ver 2.0)	250 [Kbps]	50-100[Mbps] (480 [Mbps] under short range)	• 54 [Mbps] (802.11a) • 11 [Mbps] (802.11b) • 54 [Mbps] (802.11g)
Network Range	Up to 100 [m] – effective up to 10 [m]	Up to 70 [m] (effective at 20 [m])	Up to 20 [m] (effective at 10 [m]	Up to 100 [m] (effective at 50 [m])
Main Usage	Voice applications (cell phone)	• Sensors/Control applications • Grand Scale Automation • Remote Control	• Multimedia applications • Healthcare applications	• Office and home networks • WLAN • Replace Ethernet cable
Advantages	• Highly Used • Easy Synching • Frequency Hopping Tech.	• Static Network • Control/Sensor • Many device/nodes • Small data packets • Low duty cycle • Low Power	• Easy and cheap to build • Consume very little power • Provides high bandwidth • Broad spectrum of frequencies	• Dominating WLAN tech • Know how

			(robustness)	
Disadvantages	• Interference w/ Wi-Fi • Consumes moderate amount of power	Low bandwidth	• Short range • Interference	Traditionally consumes high power
Current Automotive Application	• Portable devices • Diagnostic tools • Real time communications • Device Connectivity	• In-vehicle communication • Mobile/static sensor networks	• Robust vehicle communications • High Bandwidth communications	• Inter-vehicle communications • Vehicle-to-vehicle • Vehicle-to-Roadside

All characteristics of the competing technologies can be seen in Table 2.1. The disadvantages for the wireless protocols presented range from low bandwidth to high power consumption. Bluetooth currently maxes out its bandwidth capabilities at 3 [Mbps] with upgrades up to 12 [Mbps] possible, and offers the added complexity of having multiple external devices sharing the same protocol, such as cell phones and music devices. ZigBee's major drawback is overall bandwidth capabilities at only 250 [Kbps] which is not ideal for a sensory/controls system. Wi-Fi's disadvantage stems at its high power consumption due to its inherent use in homes and offices, rather than in energy conserving automobiles.

2.6. Hub Motors

With the ongoing push towards electric vehicles such as plug-in hybrids, hybrid with petroleum generators, and pure electric, changing the Pontiac Solstices power train is an avenue of exploration that has the possibility to literally electrify the vehicle to a new level. With the advancements in efficiency of today's AC Brushless motors, as well as cost reductions in mass manufacturing, electric drive seems to be the power train of the future. There are primarily two options for electric drive, a singular mounted electric power motor which through a transaxle can power 2 or 4 wheels, or a multiple motor setup which allows for pure independent drive with a motor at every wheel. By moving the motors to the hub location of the vehicle, it eliminates the need for a transmission, axles and the use of conventional brakes. The space that is freed up can be used for additional storage or for long range battery packs. This feature lends itself well to the architecture of the Pontiac Solstice, being a 2-seater and having only 2.1 [cu.ft] of cargo capacity, the ability to offer additional room is a customer oriented design goal. By eliminating the ECOTEC® 2.4L engine and replacing it with in-wheel hub motors, the front engine compartment can be utilized for additional storage capacity. If converted to 100% electric, the rear gas tank could also be removed and replaced with high capacity Li-ion battery packs. The battery packs could be oriented in a fashion to remove the large bulge (Figure 2.13) occupying most of the trunk capacity, making for a more available cargo storage area. For optimum weight distribution, both these areas could be populated with batteries in the lower cavities allowing for the upper cavities to be used as storage space [30]

Figure 2.13 - Pontiac Solstice Trunk with Gas Tank bulge [35]

This would allow for two things to occur: maintaining the near 50/50 weight distribution and allowing the storage cabins to be ergonomically accessible to the user.

Available power in the Solstice would be another concern for a sports car enthusiast. The 4 cylinder, ECOTEC® 2.4L with Variable Valve Timing DOHC offers 173 [hp] (129.0 [kW]) @ 5800 [rpm] and 167 [lb-ft] of torque (226.0 [N-m]) @ 4500 [rpm].

The base engine in the Solstice offers a sufficient amount of power for a car its size with that stated despite the Solstice's small size it surmounts to a curb weight of 1297 [kg] (2860 [lbs]) which translates to a 16.53 weight to power ratio. For comparison, a high end sports car like the 2007 Corvette has a weight to power ratio of 7.95 and a four door sedan such as the Impala LTZ has a ratio of 15.19. From this we can see that the Solstice is underpowered for a performance oriented enthusiasts vehicle.

In 2007 the Pontiac Solstice was offered in GXP trim which offered a Turbo ECOTEC® 2.0L Variable Valve Timing DOHC 4-cylinder engine. This turbocharged engine increased the power output of the base engine by 83 horsepower, offering a total of 260 [hp] (193.9 [kW]) @ 5300 [rpm], and 260 [lb-ft] of torque (351.0 [N-m]) @ 2500 – 5250 [rpm]. Although the GXP edition increased power output the curb weight also increased due to the added turbocharger components, the total weight increased by 53 [kg] (116[lbs]) to a total of 1350[kg] (2976[lbs]) The power and slight weight increase yields the GXP Solstice a weight to power ratio of 11.4, a much more respectable number for a performance roadster.

With a brief comparison between the two available spark ignition engines for the current vintage Solstice (2007) and with a possible drive-by-wire setup utilizing in wheel motors the gains are evident see Table 2.2. TM4, a company based in Quebec Canada, offers a unique hub style motor that minimizes space requirements, is direct drive and is highly efficient. TM4 claims they can make a motor for individual needs of a vehicle, to fit the space and power requirements a customer requests. The motors utilized are brushless AC and are liquid cooled, which combines the best combination for overall reliability and long term performance. The TM4 Transport Motor Wheel System in-wheel hub electric motors (Figure 2.13) offer amazing power at low RPM's.

Table 2.2 - Solstice Engine vs Independent Electric

Engine Type	Solstice XP Turbo ECOTEC® 2.0L	Solstice Base Model ECOTEC® 2.4L	TM4 Transport Motor Wheel System [36]
Power Output [hp]	260	173	107 x 4 = 428
Torque Output [lb-ft]	260	167	494
Weight [lbs]	2976	2860	~ 3200 [lb] electric Solstice
Weight/Power Ratio	11.4	16.53	7
Transmission Req.	5 spd manual/auto	5 spd manual/auto	N/A
Power Adder	Turbo	None	None
Regenerative Braking	N/A	N/A	Yes
Cooling	Liquid	Liquid	Liquid
Fuel/Energy Source	Gasoline-87 octane	Gasoline–87 Octane	Electric – Battery Max 500 [V]
Drive Configuration	Rear-Wheel-Drive	Rear-Wheel-Drive	All-Wheel-Drive
Differential	Limited Slip	N/A	Independent Drive
Drive-by-wire ready	TbW	TbW	All
Efficiency	19/25 (city/ highway) [mpg]	19/28 (city/highway) [mpg]	Efficiency under continuous load @ 950 [rpm] 96.3%

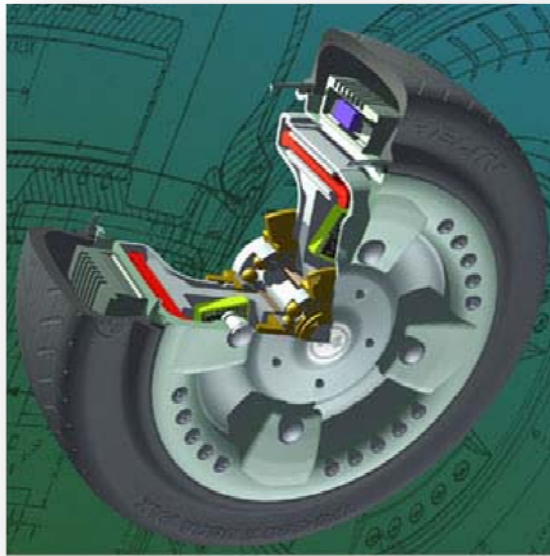


Figure 2.14 - TM4 Hub Motor Configuration [37]

Currently, in industry hub motors are utilized in large ore mining trucks. Only the largest of trucks utilize an in wheel setup. The setup consists of a diesel engine that drives an A/C generator that provides electric current to a solid state electric power converter. The electric power converter is an A/C to D/C converter which supplies power to large electric wheel motors which are housed inside the massive mine truck's wheels. The motors transfer their power through a planetary gear drive to reduce the speed of the motors efficiently in order to minimize the speed and maximize the torque of the large trucks. The advantages of having the wheel motor setup is that the truck has full control over each individual wheel and can detect wheel spin or slippage which then can be reduced by cutting power [38].

The D/C drives were the start of the utilizing wheel motors in the mining industry. The D/C drives were able to handle up to 240 [S/T] on the diesel electric trucks. The even larger 360 [S/T] trucks were equipped with high-power A/C inverters to supply power to induction A/C drives. The newly developed three-phase induction motors were able to offer high reliability, continuous operation along with high shock and vibration resistance. This combination enabled the large ore mining truck to have a high starting torque, higher efficiencies all while offering a smooth stepless operation in motoring and or braking at full speeds [39]. Currently, General Electric (GE) has released a hybrid mining truck that utilizes an A/C drive system that has evolved from systems used in current locomotive technologies (see Figure 2.15) [40].

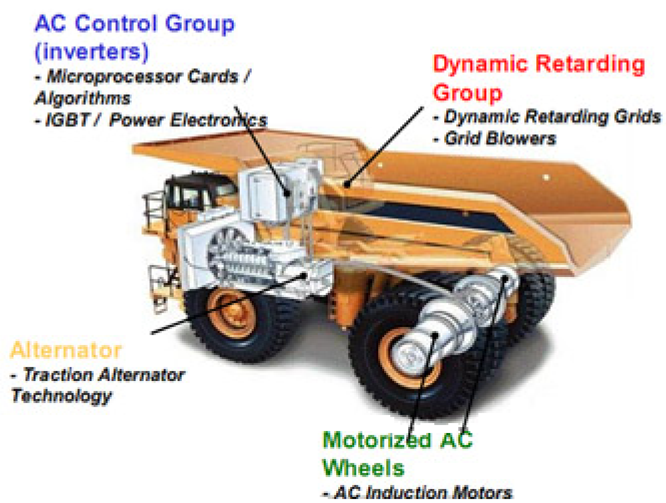


Figure 2.15 - GE Hybrid Mining Truck utilizing AC Wheel Motors [40]

2.7. Summary on Current Technologies

By-Wire systems have a future in the automotive industry for a multitude of reasons. These identical reasons can be correlated with why it is feasible to implement by-wire braking, by-wire hub motors and by-wire steering into the Pontiac Solstice.

These reasons include:

- Increased efficiency
- Safety via Adaptive controls

- Decrease production costs
- Facilitate future electric technologies, hybrid, fuel cell
- Connects with emerging systems, such as adaptive cruise control
- Reduces system weight to provide improved vehicle performance and economy
- Assembles the system into the host vehicle simpler and faster
- Reduces pollutant sources by eliminating corrosive, toxic hydraulic fluids
- Removes the vacuum servo and hydraulic system for flexible placement of components
- Reduces maintenance requirements
- Supports features such as hill hold.
- Removes mechanical components for freedom of design
- Eliminates the need for pneumatic vacuum booster systems

From this definitive list, it is clear to see why by-wire technology is suitable for any vehicle and not just the Pontiac Solstice.

Chapter 3 Design Problem Statement

3.1 Preliminary By-wire Design Considerations

In order to develop a new product, or to improve upon an existing product it is imperative that the customers' needs and wants are identified, weighted and analyzed with currently available technologies or products. To do this accurately and in an organized easily displayed manner Quality Functional Deployment (QFD) tools and techniques, such as the House of Quality (HofQ) matrix have to be used.

The HofQ technique identifies customers' needs and wants and puts a strong voice of the customer (VOC) into analysis of the current product. Then, engineering specifications for the product are identified to meet the wants and needs of the VOC. Each category is then weighted by the customer, and then is graded on compliance from the engineering specifications that it meets or fails to meet. By completing this technique the customers' needs can be translated into engineering characteristics which then can be targeted in the development or improvement of a product. In this analysis the customer is not only considered as the ultimate purchaser of the product, but also the manufacturer. It is important to take into consideration both manufacturability of the product being assessed as well as assembly of the product into the vehicle itself. This will ensure that all processes are optimized and consideration for each characteristic will be considered and evaluated at a very early design stage [41].

Two components of the drive-by-wire system will be analyzed by using the HofQ matrix; steer-by-wire controls and brake-by-wire controls. The steer-by-wire analysis will be between the existing Pontiac Solstices rack and pinion architecture, SKF's steer-by-wire electromechanical system and with Delphi's Quadrasteer four wheel steering system. On the other hand, brake-by-wire examination will be evaluated between the Solstice's OEM hydraulic system, Siemens VDO's Wedge style braking system, and with Newtech's full contact braking system.

In Table 3.1, the planning matrix for the Drive-by-wire braking is displayed, showing how customers' voices can be translated directly into engineering characteristics. It can be seen that performance characteristics on the Solstice will need to be maintained or improved, however this should have no detrimental effect on the reliability or safety of the SbW system as this is the number one customer concern.

Overall, the Siemens VDO braking system is the most suitable for the Pontiac Solstice. It offers a brake-by-wire solution, sufficiently better stopping power, truly independent wheel braking all in a package that is truly dry with no hydraulic fluid needed.

The Newtech full contact braking system would be too much for a small vehicle such as the Solstice, and would deliver stopping power that the average performance enthusiast would consider above and beyond the needs of the vehicle.

The Steer-by-wire analysis was very definitive although luxury perks such as height adjust, tilt adjust and telescopic column were mildly important to the customer. However characteristics such as turning ratio and lock to lock wheel ratio were necessities that could not be comprised when converting to a by-wire system. Table 3.2 showcases the comparison utilizing the QFD House of Quality analysis. The SKF system is the most flexible to the customer's needs. It also offers flexibility in installation, with the inherent loss of the steering column, assembly simplifies to installing the rack, and the controls.

However, the Quadrasteer system tackles the issue of having the very best in turning performance, with the ability to turn the rear wheels and achieve a turning radius nearly 30% less than the stock OEM’s system.

Table 3.1 - DbW QFD House of Quality Analysis

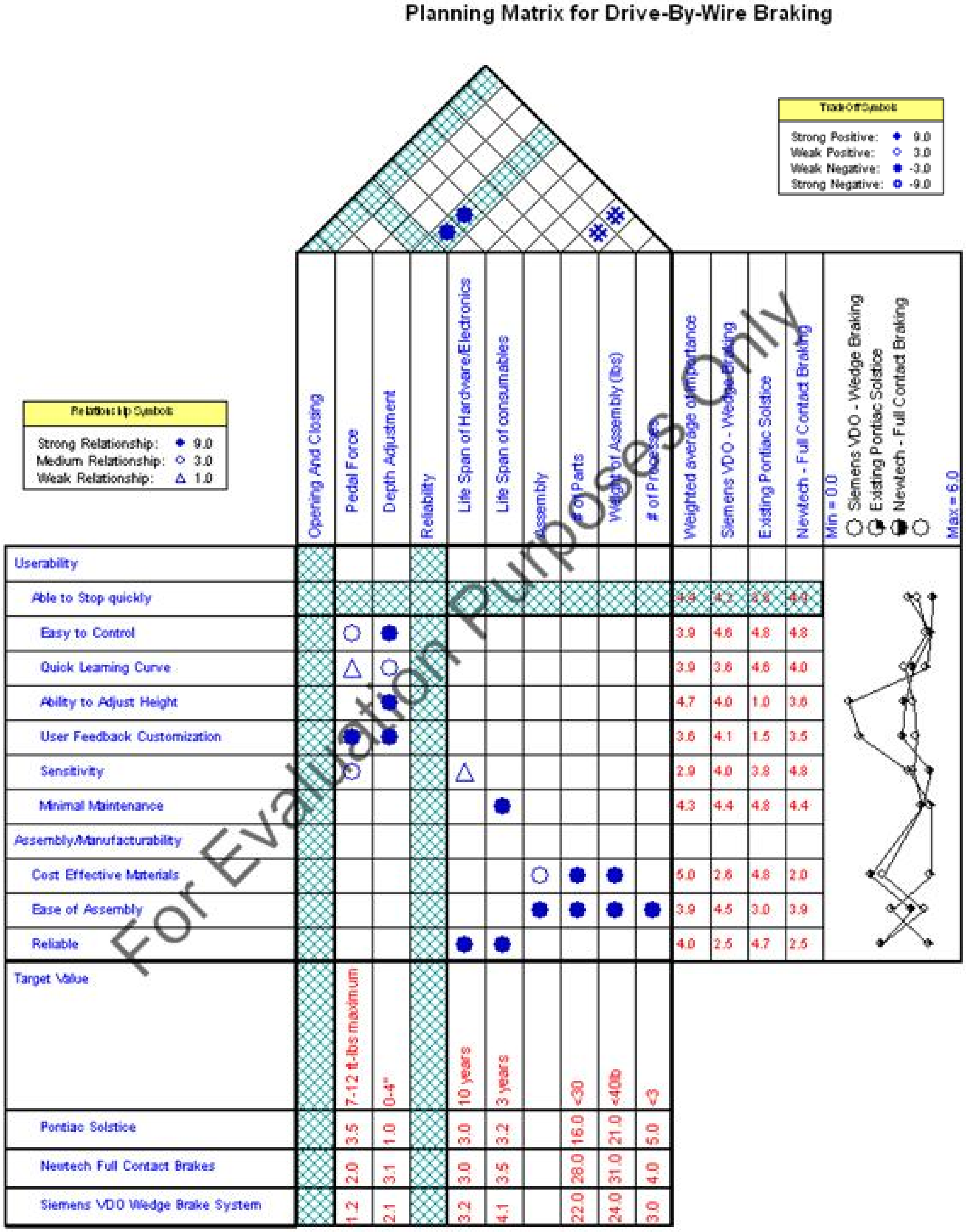


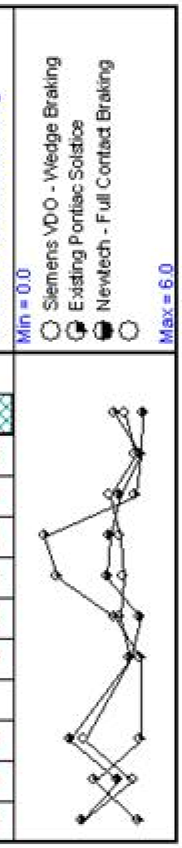
Table 3.2 - SbW QFD House of Quality Analysis

Planning Matrix for Drive-By-Wire Braking

Trade Off Symbols		
Strong Positive:	◆	9.0
Weak Positive:	◇	3.0
Weak Negative:	✱	-3.0
Strong Negative:	✲	-9.0

Relationship Symbols		
Strong Relationship:	●	9.0
Medium Relationship:	○	3.0
Weak Relationship:	△	1.0

	Opening And Closing	Pedal Force	Depth Adjustment	Reliability	Life Span of Hardware/Electronics	Life Span of consumables	Assembly	# of Parts	Weight of Assembly (lbs)	# of Processes	Weighted average of importance	Siemens VDO - Wedge Braking	Existing Pontiac Solstice	Newtech - Full Contact Braking
Userability														
Able to Stop quickly											4.4	4.2	3.8	4.0
Easy to Control		○	●								3.9	4.6	4.8	4.8
Quick Learning Curve		△	○								3.9	3.6	4.6	4.0
Ability to Adjust Height			●								4.7	4.0	1.0	3.6
User Feedback Customization		●	●								3.6	4.1	1.5	3.5
Sensitivity		○			△						2.9	4.0	3.8	4.8
Minimal Maintenance						●					4.3	4.4	4.8	4.4
Assembly/Manufacturability														
Cost Effective Materials							○	●	●		5.0	2.6	4.8	2.0
Ease of Assembly							●	●	●	●	3.9	4.5	3.0	3.9
Reliable					●	●					4.0	2.5	4.7	2.5
Target Value		7-12 ft-lbs maximum	0-4"		10 years	3 years		<30	<40lb	<3				
Pontiac Solstice		3.5	1.0		3.0	3.2		16.0	21.0	5.0				
Newtech Full Contact Brakes		2.0	3.1		3.0	3.5		28.0	31.0	4.0				
Siemens VDO Wedge Brake System		1.2	2.1		3.2	4.1		22.0	24.0	3.0				



Another option not discussed that would combine the flexibilities of both units would be a vertically mounted electric motor affixed to the strut bearing, that would allow independent control to all wheels. The complexity would increase due to two extra motors; however the introduction to more space and elimination of racks and pinions would be an asset due to the space constraints within the Solstices chassis.

3.2 Preliminary Drivetrain Design Considerations

The baja style dune buggy (Figure 1.8) was chosen as a test bed vehicle. The vehicle would be a joint project that consists of converting the supplied 250cc, carburated, single cylinder, 4-stroke, internal combustion engine (ICE) to a hydrogen combustion engine that would in turn be a generator and supply power to a battery array. The objective is to have a series hybrid vehicle with hydrogen as the generators fuel, coupled with a simulated hub motor drive train and electronic differential [42]. The vehicle came equipped with a continuously variable transmission (CVT) mated to a rear differential setup. It had a top speed of 80 [km/h] and reached that speed in 12 seconds. Complete specifications of the original test vehicle are listed in Table 1.1.

A prototype hybrid electric vehicle based on the dune buggy is needed to be built. The motors would be fitted to the prototype vehicle in a hub based fashion and an electronic differential control system would be added. By-wire technology would be implemented on the brakes and the throttle. Once all modifications will be made to the vehicle and all design objectives will be implemented, the vehicle's performance should be expected to meet (or exceed) the original OEM specifications. It is assumed that a drastic increase in vehicle mass will be needed in order to achieve all design parameters listed.

The initial testing of the vehicle yielded performance results less than exciting for a vehicle built for off-road entertainment and such performance would be increased in the test vehicle. The vehicle performed a 0-60 [km/h] test in over 20 seconds and seemed to perform in a non-consistent manner from test to test. Handling characteristics as well as overall ride quality were recorded during test drives for subsequent comparison with the modified version.

The key reason for exploring, developing and analyzing a near wheel architecture is to eliminate the inefficiencies presented in today's internal combustion engine (ICE) petroleum vehicles. In order to maximize total vehicle efficiency, losses in current architectures were analyzed and targeted. A current combustion gasoline powered vehicle will achieve around 28 EPA adjusted [mpg], or 8.4 litres of fuel per 100 [km] on relatively level city streets. The fuel that is burned is not 100% converted into energy to propel the vehicle, the actual percentage is quiet surprisingly low. To analyze this fact further it has been shown that 85-87% is lost to heat and noise in the powertrain, including engine, pollution controls and the mechanical drivetrain [43]. These losses are contributed to the effects of friction, characteristics of the combustion process, aerodynamics, and idling.

Figure 3.1 shows where the losses are derived from and which losses compose the majority of the inefficiencies of the conversion of energy to moving the vehicle. The figure summates the 85%-87% of the losses in an ICE vehicle in order to visualize where the losses are derived from. The standard ICE is approximately only 35-38% efficient showing a 62% loss which is the largest of all the losses. The second largest loss is that of idling the car with no movement at all with a total of 17% loss on average while driving. Thirdly, drivetrain losses account for 6% of the total losses, which include transmissions, drive shafts, and differentials, this figure increases with all-wheel-drive vehicles.

The three losses of ICE energy loss, idling losses and drivetrain loss are the main concentrations of the research and development contained in this thesis. The reduction or preferably the elimination of these losses is paramount to increase the efficiencies of the everyday automobile. The elimination of these losses will be performed by converting the vehicle to an all electric drivetrain, targeting the losses contributed to gasoline engines and idling losses and implementing a direct drive setup to target drivetrain losses.

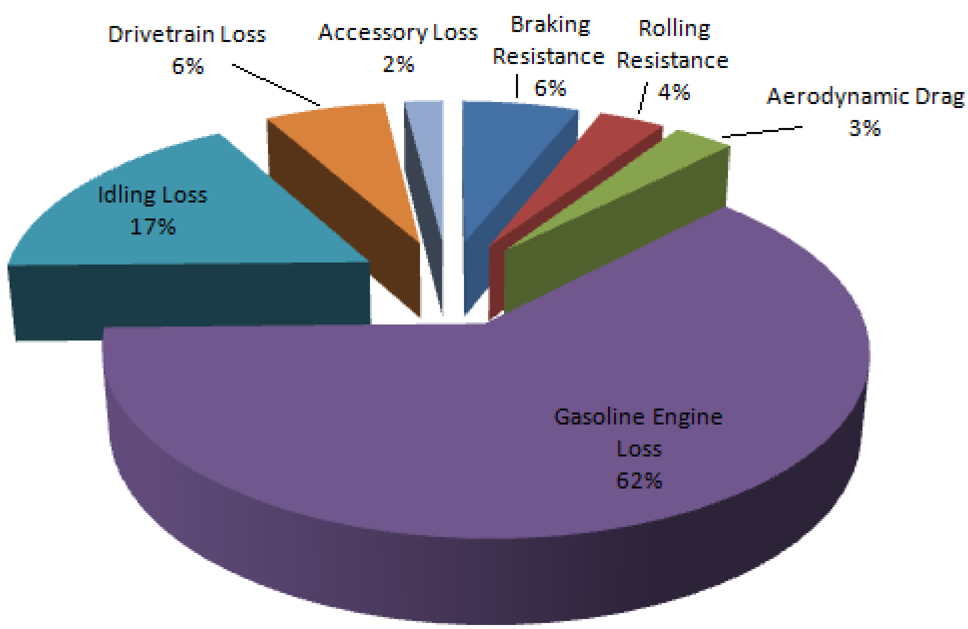


Figure 3.1 - Losses in a Common ICE Powered Automobile [43]

The remainder of the losses are attributed to tractive loads such as 6% for braking resistance, 5% for rolling resistance as well as 3% for aerodynamic drag. The thesis will target braking resistance by implementing regenerative braking, although it will not be the main focus of the research project.

To eliminate the losses posed by the transmission of power, an alternative solution is needed to utilize direct drive orientation – by fitting a motor directly to the wheel itself or incorporating the motor within the wheel itself, the losses of mechanical transfer devices such as transmission would be eliminated.

Additional advantages of a direct drive system include: direct control of individual wheels along with possible closed loop control of each individual wheel, true all wheel drive setups when a motor is affixed to all four individual wheels, and possible advancements in stability/traction control systems due to the increased control that a direct drive system offers. The mass factor is also reduced by removing transmission and differential components. The positioning of the motors at the four corners of the vehicle also offers the enhancement of equal weight distribution to become closer to the ideal 50/50 distribution of today's sports cars.

3.3 Design Project Management Approach

The electrification of the modern day automobile provides many opportunities for innovative improvements over today's internal combustion (IC) vehicle. The onset of electric technologies has triggered much architecture to emerge in coupling electric motors into the existing power trains of IC vehicles. Such approaches include transaxle mounted electric motors as found in the do-it-yourself (DIY) community and parallel/series hybrid power train arrangements as seen in today's OEM market. Series and parallel arrangements offer the benefit to be able to switch between power sources. All, however, still infringe on existing interior space constraints of today's passenger vehicles as well as utilizing many inefficient mechanical power transfer devices which do not apply power directly to the wheels. By incorporating a hub motor or near wheel motor design, these interior space constraints are no longer a consideration as the entire power train has been moved outboard to a location of power transfer; the wheels. The design flexibility of inboard space will be increased dramatically and will have the potential to be used more effectively rather than for the storage of the engine. With such changes mechanical efficiencies are also introduced by the elimination of such power transfer devices.

The initial design for near wheel mounting assembly for this project was accomplished concurrently with a group of undergraduate students under the guidance of graduate students. An engineering management approach was taken with the undergraduate students playing the role of a contracted engineering group and the author as the engineering manager or customer. The design outline was provided to the students to create a design that was guided by the author. The outline provided to the students is provided in Appendix B. Undergraduate Project Scope – First Design Iteration. Throughout the design process the students were coached and suggestions were given in order to optimize the final solution in the first iteration of design, however no restrictions were placed on the level of innovation, the design steps taken to create a final solution, or the level of innovation and creativity in the solution presented. Communication and feedback was given primarily in the form of e-mail, however a wiki was created in order to monitor progress throughout the project. An example of feedback from the author is presented in Appendix C. The design was developed and manufactured (Figure 3.2) in the prototype stage and has currently been installed in the Baja dune buggy for testing.

The electrics of the vehicle will need to be developed in a concurrent fashion along with the drivetrain of the vehicle. All electrical schematics and power delivery will need to be created and implemented into the test bed vehicle in order to test functionality of drivetrain components. The components will need to be analyzed for suitability as a system and selected from a set of available technologies. The layout and schematic architecture of the system will be unique to an independent rear drive vehicle. An innovative approach will be needed in order to implement a by-wireless braking system, replacing the conventional rear hydraulic disc brakes of the vehicle. The brakes should also harness the inertia losses while braking and transfer those losses to the batteries in a regenerative braking approach.

The roadmap that will be followed for the redesign of the hub motor gear box mounting assembly will be performed in a systematic approach following traditional design algorithm as shown in Figure 4.1. Since the design is in its second iteration after following another engineering team's design sequence the path followed for redesign will vary slightly from the traditional path, and will use a variety of design tools and methodologies to fulfill the steps in the design process. The current design will be reviewed and analyzed through the use of these tools and methodologies, build upon the ideas that have already been created, and possibly create a more efficient and better performing assembly.

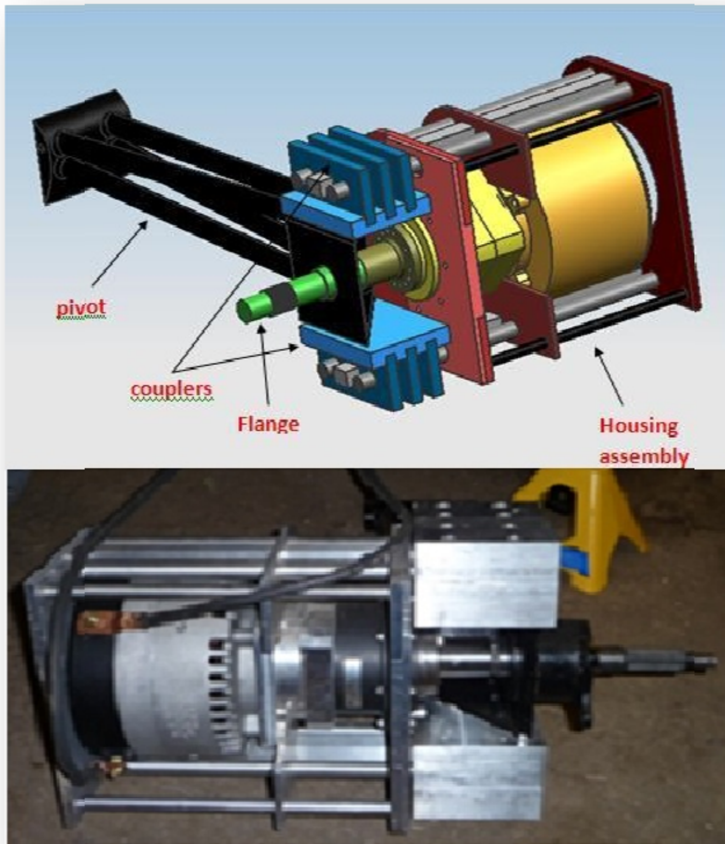


Figure 3.2 - Motor/Gearbox Mount Assembly

3.4 Innovative Contribution

The innovative contribution in this thesis project is two-fold:

1) Design and development of a compact near-wheel motor setup for a conventional motor vehicle, and

2) Design and development of by-wire/wireless braking setup for a conventional motor vehicle.

The remainder of the contributions of the thesis, although innovative in the terms of the overall system, are adaptations of existing technologies. Currently hub-motor vehicles have been briefly shown as pure prototypes, with many not exhibited as drivable vehicles. The near-wheel motor approach simulates that of a hub motor vehicle without enclosing the motor assembly into the motor itself. It combines a pancake style motor which is compact in overall volume with a high power density. Naturally, if the motors speed range and torque range is not sufficient to propel the vehicle, then a gear system would need to be affixed to the motor in order to achieve proper output speeds. It is the proposal of this thesis to mate a high power to rate ratio permanent magnet motor with a highly efficient planetary gearbox (Figure 3.3) to simulate the advantages of a hub motor however in a near wheel approach. Placing the motors directly beside the wheel eliminates the rotational mass of the motor within the spinning wheel/tire assembly.

Figure 3.3- Motor + Planetary Gearbox = Hub Motor Simulation

Another benefit of using near wheel motors is that it eliminates the need to have custom hub motors created for different wheel sizes. This also prevents any complications associated with mounting tires to the motor housing itself in the case of the removal and installation worn and new tires. In addition the motor is not subject to severe direct impacts in rough road conditions due to it being offset inboard from the wheel itself. A near wheel approach still offers a direct drive solution however the wheel/tire is fastened to the output shaft of the motor/gearbox itself, this adds the flexibility of being adaptable to all current rear drive vehicles. In the realm of automobile powertrains a near wheel motor solution as presented in this thesis would arguably be a level 4 in degree of inventiveness - A new generation of a system that entails a new principle for performing the system's primary functions [44].

Attempts have been made to create vehicles with a multitude of by-wire of technologies as outlined in Chapter 2. However by-wireless technologies have not been devised for motor vehicles. This thesis proposes to explore these technologies and offers an initial stepping stone for the testing of a wireless control system in a vehicle. The level of inventiveness is high as by-wireless technologies do not exist in vehicles nor have they been discussed in the prototyping stage of vehicle development. The purpose of developing this control architecture within a vehicle is to allow for the very cutting edge of the technology to be presented, tested and evaluated.

Chapter 4 Design Problem Solution

4.1 Design Process

The design path that this project will follow starts with failure mode and effect analysis (FMEA) [31] of the current design, listed as 1) in Figure 4.1. This will take place nearly ¾ of the way through the design cycle. As the design presented has reached the end of the embodiment stage it is not, however, ready for detailed design as many improvements can still be made. Furthermore, the current prototype is by no means the completion of the design cycle, but somewhere in the middle, ready for further iterations.

The FMEA analysis will evaluate and dissect all fundamental design parameters and identify any failure modes that may exist. This will reduce the chances that a failure would reach any future customer. The FMEA study will show the overall effects of possible failures and their consequences to the end customer.

Following the FMEA analysis, a rigidity analysis on the current design will be performed (#2 in Figure 4.1). A Rigidity Index will be calculated to understand the overall flexibility of the current design and to understand which design parameters and characteristics are critical in making the design perform. The rigidity analysis will be used as a benchmark to compare future design iterations. It will also allow for a further understanding of the relationship of the design parameters [41].

The design cycle process now leads to the start of the design chain. The 'need analysis' found in Figure 4.1 #3 will be re-evaluated. The tool used to perform the evaluation of the 'need analysis' will be the Pugh generation-selection matrix methodology [41]. It is crucial in any design cycle to ensure that the customer's needs are met, and that the proper solution is targeting the proper need. Without a solid basis on what the customer need is any design solution no matter how innovative or creative will be a failure if it does not target the direct needs of the customer.

Once the needs of the customer are addressed a generalization of ideas will take place with the help of the TRIZ methodology (see Figure 4.1 - #4). TRIZ is a valuable tool for creating inventive solutions to new problems but can also be in the refinement of old systems [41]. The 39 Design Parameters of TRIZ will be listed and associated with the current design to give a genuine understanding of how the design ideas generated will relate to fundamental design parameters. Secondly, the 40 TRIZ principles will be reviewed and used as a basis for improvement on the new design. The 40 TRIZ principles will be used as a creative design tool in order to analyze all possible areas of the design to enable improvements which were authorize left static [41].

Lastly, the Rigidity Index will be recalculated (see Figure 4.1 - #5) with the newly formed design as the subject. This newly formed design would be the result of the previous design methodologies. The newly calculated Rigidity Index will be compared with the original benchmark to see if any improvement on the overall design should be made.

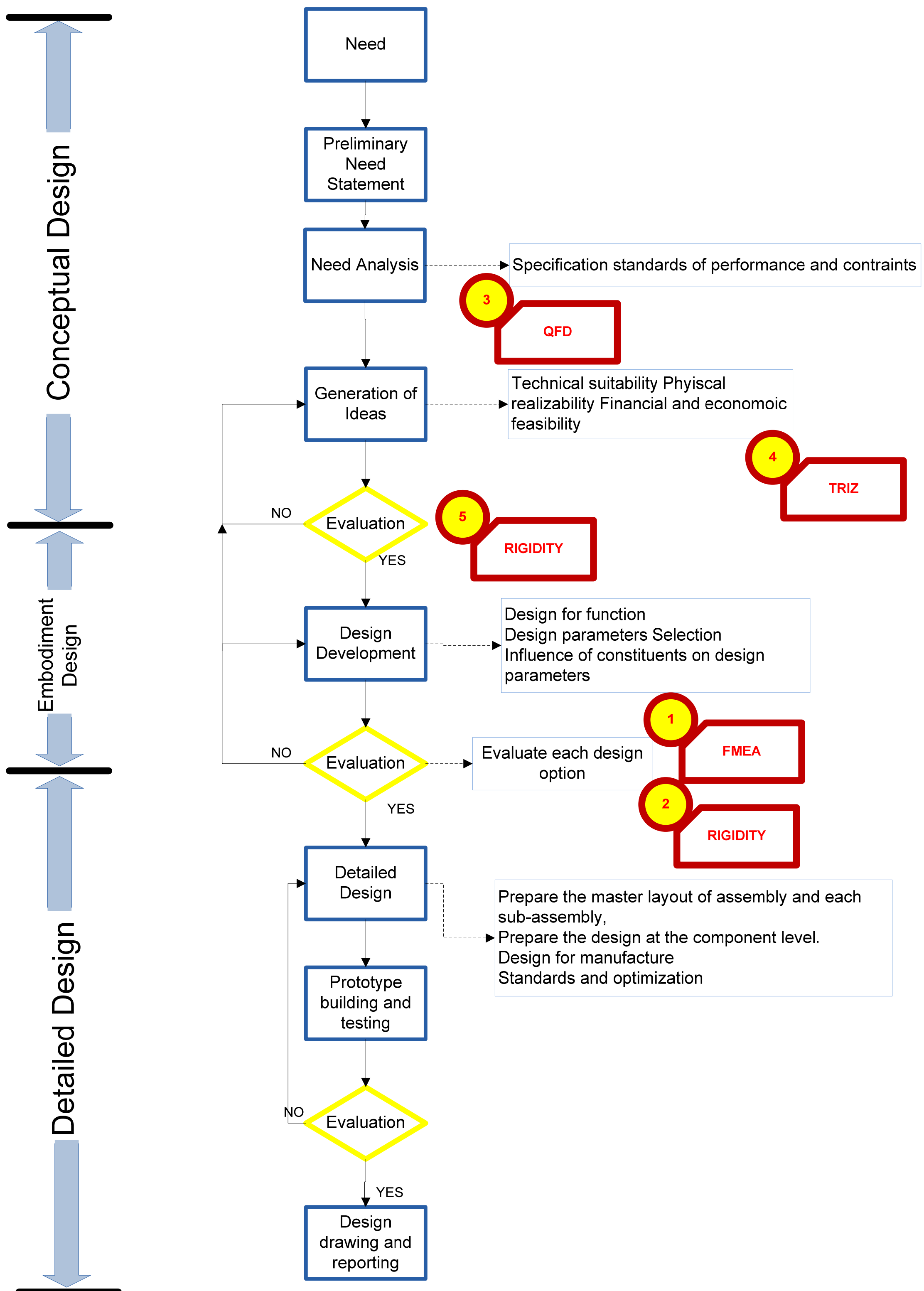


Figure 4.1 - Modified Sequence of Design Activities (adopted from ref. [42])

4.2 Concept Generation of Near Wheel Mounting Assembly

Various concepts were considered and generated in multiple ways. The team met for brainstorming sessions to generate ideas. Everyone would then dissolve into an individual setting to generate further ideas, expanding on the ideas that were formed as a group. After several meetings and discussions the following ideas (discussed in this section) were formed into 3D models for a better understanding of how the ideas brought forth fit the concept vehicle as an entire assembly.

The idea of space saving comes to mind when thinking of a hub wheel motor setup. Thus a 90° concept was formed, by connecting a 90° planetary gear box to the hub and allowing the motor to mount vertically as opposed to the traditional horizontal mount. Central space in the vehicle would be further optimized with this approach as the motor would occupy the vertical space beside the tire.

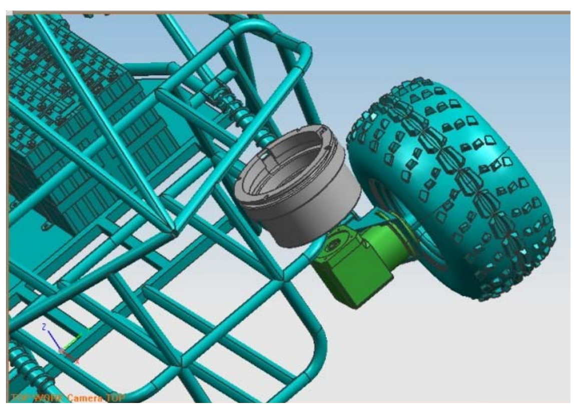


Figure 4.2 - 90° Vertical Motor Mount

The idea of creating a uniform case (see Figure 4.3) for the entire motor and gearbox assembly was generated. This design would mount into the modified suspension of the existing vehicle. The housing would double as a shield from the elements as well as a structure to support the entire assembly. Modifications to the housing would have to be made to optimize air flow for cooling and prevent water from entering the housing.

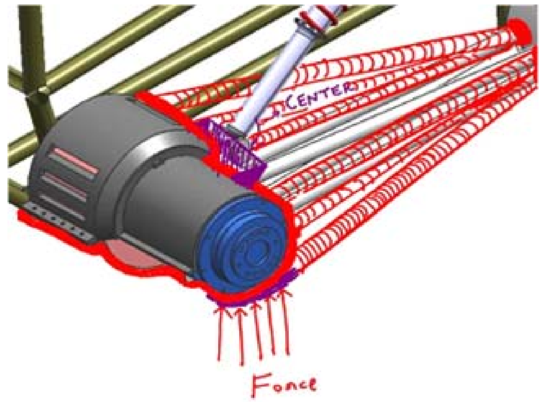


Figure 4.3 - Motor Gearbox Case Shield

A simple “C” channel bracket (see Figure 4.4) was also thought of as a viable concept. The bracket would span the length from the motor to the end of the planetary gearbox. The mounting locations would be at the motor housing mounting bolts, and on the secondary coupling of the gearbox. The entire assembly would be ‘sandwiched’ into place.

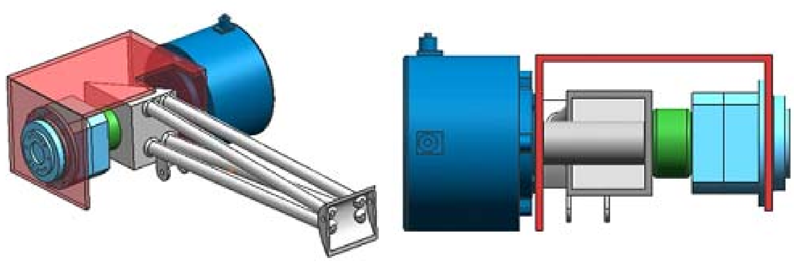


Figure 4.4 - "C" Channel Bracket

Several discussions were made in regards to have a ‘non-solid’ or porous type of housing for the gearbox and motor composed of channel bar that would attach to the motor and gearbox via ring mounts (see Figure 4.5). The channel bar would be secured to the ring mounts by sliding each bar into place, with a set screw type of locking mechanism to ensure the channels do not move. Pictured in Figure 4.5 are the 3 rings; one around the back of the motor, one around the front of the motor and one around the gearbox.

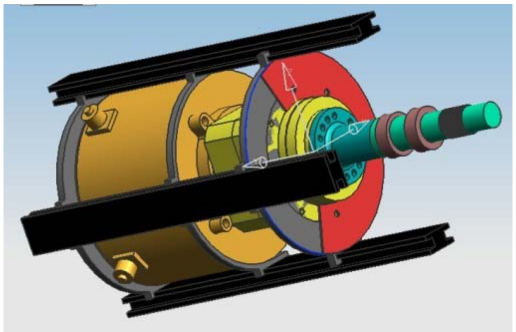


Figure 4.5 - Channel Bar Housing

Finally a design was developed that was ready for concept prototype evaluation (see Figure 4.6). It encompasses several of the key aspects of the previous prototypes including a channel based solution, with multiple support plates. Also, it leaves the gearbox and motor open for easy assembly and disassembly. The entire structure is composed of 6061 aluminum to keep weight down without sacrificing robustness. The solution to mounting the gear boxes consisted of several tubular support braces surrounding the motor and gearbox assembly, with 3 cross plates for stability. Hub mounting blocks were added to the vehicles hub assembly so that the entire assembly could be easily dismounted.

This design is the target for redesign in this project and will subject to the methodologies mentioned in Section 4.1.

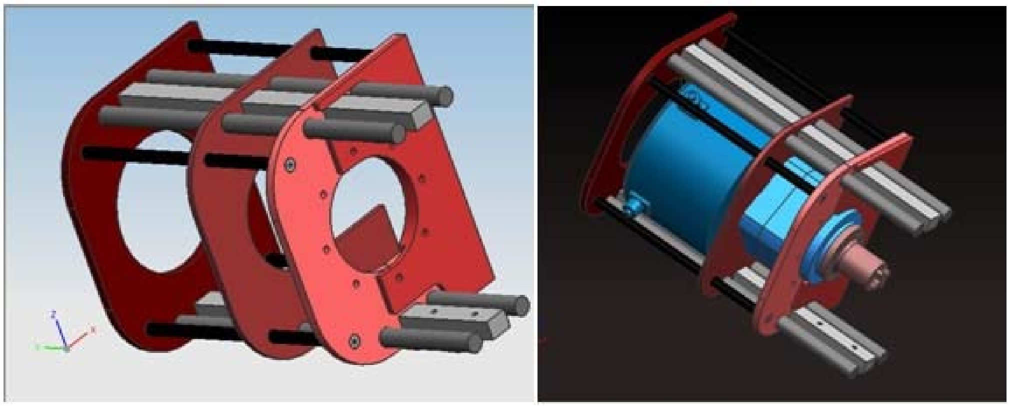


Figure 4.6 - Final Prototype Concept Design - Iteration #1

4.3 System FMEA

Failure modes and effects analysis is a procedure to analyze potential failure modes within a design that may affect the customer directly or indirectly. Failure modes in the design are classified as any errors or defects that the process may have or may appear. The analysis of these failures studies the consequences and possible measures to resolve them. The current design was analyzed by all members of the design team and a list of concerns or possible failure modes was created. First, the functional requirement was listed, than the corresponding failure mode was recorded. After the requirement and the failure mode have been associated, the effect that the failure would have on the customer was studied and listed.

Table 4.1 - Severity Ranking - FMEA

Ranking	Criteria
1	Unreasonable to expect that the minor nature of this failure would cause any noticeable effect on the product quality. Customer probably will not be able to detect failure.
2 3	Low severity ranking due to minor nature of failure causing only slight customer annoyance. Customer will not notice any system performance change or quality loss.
4 5 6	Moderate failure which causes some customer dissatisfaction. Customer is made uncomfortable or is annoyed by the failure. Customer will notice some system performance degradation or quality loss.
7 8	High degree of customer dissatisfaction due to the nature of the failure.
9 10	Very high severity ranking when a failure involves potential safety problems or conformance to specifications.

The severity (Sev) ranking of the failure is based on scale of 1 through 10. With 1 being unreasonable to expect that the minor nature of this failure would cause any noticeable effect on the product quality. Also, the customer probably will not be able to detect failure. The ranking 10 would indicate a very high severity ranking when a failure involves potential safety problems or conformance to specifications. The rankings can be seen in Table 4.1.

The occurrence (Occ) value in Table 4.2 refers to the probability that the specific failure mode will indeed fail. The ranking scale ranges from 1 to 10 and has been determined by a survey of subject matter experts (SME) associated with the project. The number of votes the SME's had for the probability of each failure mode occurring was recorded and then tabulated from the table to its associated ranking number.

Table 4.2 - FMEA Occurrence Ranking

		Possible Failure Occurrence Rates	
Ranking	Criteria	SME Votes	Probabilities of Occurrence
1	Remote possibility of occurrence. It would be unreasonable to expect the failure to occur.	0-1	0-5%
2 3	Low failure rate. Generally associated with similar processes having relatively low number of failures.	2	5-40%
4 5 6	Moderate failure rate. Generally associated with similar processes which have experienced occasional failures, but not in major proportions.	3	40-70
7 8	High failure rate associated with failures of similar processes that have traditionally caused problems in the past.	4	70-85%
9 10	Very high failure rate. Almost certain that failure will occur in major proportions.	5+	85-100%

The last metric used was detection (Det). The table associated with this value is Table 4.3 and is the metric responsible for ranking how noticeable the failure mode is when it has failed. The detection ranking is important because even though a portion of the design may have failed, there may be a possibility that the customer cannot detect that it has failed, or would not necessarily be bothered if it has failed. This ranking is completely subject to the customer and has been determined through the authors individual opinion and knowledge of the design being offered.

Table 4.3 - FMEA Detection Ranking

Ranking	Criteria	Probability of Defect Reaching the Customer
1	Remote likelihood that the defect will not be detected before occurrence - it will not reach the customer.	0-5%
2 3	Low likelihood that the defect will not be detected before occurrence - it will probably not reach the customer.	6-15% 16-25%
4 5 6	Moderate likelihood that the defect will not be detected before occurrence - it may reach the customer.	26-35% 36-45% 46-55%
7 8	High likelihood that the defect will not be detected before occurrence - it probably will reach the customer.	56-65% 66-75%
9 10	Very high likelihood that the defect will not be detected before occurrence - it will reach the customer.	76-85% 86-100%

Table 4.4 - FMEA Table

POTENTIAL FAILURE MODE AND EFFECTS ANALYSIS

Page 1 of 1

Original FMEA Date 01/04/2009

Prepared by Mark Bernacki

Telephone #

Component - Hub and Motor support for Hub motor simulation.

FMEA Revision Date April 6th, 2009

Design Item or Process Function Requirements	Potential Failure Mode	Potential Effect(s) of Failure	Sev	Potential Cause(s) / Mechanism(s) of Failure	Occ	Current Design or ProcessControls	Det	RPN	Recommended Actions	Responsibility & Target Completion Date	Actions Taken	Sev	Occ	Det	RPN
Hub Mount structure + weight of components should weigh less then 50lbs	Suspension will not compensate for large increases in unsprung mass	Loss of control due to lack of dampening from suspension, poor ride due to shutter from suspension	10	Insufficient OEM suspension design for increased unsprung mass. Unsprung Mass too high for hub design	9	None - Weighs 67lbs	8	720	Less material should be used to build structure. Support components should not extend past motor/gearbox flange	Design Team / April 31st '09	Complex structure replaced with angled bracket, including brace for gearbox to be mounted directly to. As well existing hub assembly has been removed. New suspension has been ordered with finite adjustments to dampening. Nitrogen Baja shocks	10	2	3	60
Hub Mount structure should be supported securely	Large free standing structure mounted at a single point has a large possibility of breaking during harsh conditions of driving on uneven surfaces	Structure breaking during real road testing due to vibration and force from suspension movement	10	Mounting interface for gearbox and motor housing to hub not correctly engineered for the harsh elements of driving on uneven surfaces, vibrations, jerks etc	5	Finite element analysis performed, structure aluminum bars used as support to hub mount	6	300	New design for compression insert design and aluminum rods. Possible solid mounting device used such as a bolted bracket.	Design Team / April 31st '09	Structure is condensed and very solid, similar to OEM design in overall strength, all with positive locking mechanism such as welds and bolts.	10	3	4	120
Redesign should minimize weight of existing vehicle structure to further reduce unsprung weight	Suspension will respond more effectively with a reduced unsprung weight	Loss of performance and adverse handling characteristics due to undampened masses.	8	Insufficient OEM suspension design for increased unsprung mass. Unsprung Mass too high for hub design	10	None - Current design made no changes to existing structure except for removing rear brake components	10	800	Redesign Hub assembly of existing vehicle, or possibly remove all together.	Design Team / April 31st '09	Hub assembly and bearing has been removed and planetary gearbox will suffice as replacement mounted on to the newly engineered bracket.	8	2	6	96
Assembly and dissembly should be easy to perform	If a component fails or needs to be evaluated dissassembly and reassembly will need to occur	Potentional costly and timely repairs if/when component failure or maintenance occurs.	4	No use of DFM or DFA in initial design process	6	Currently can be disassembled with allen key wrench, compression hub mounts difficult to assemble/disassemble and some interference for bolt entrance	3	72	Intricate design requires intricate assembly/disassembly. Simplify design to allow for easier assembly and repair.	Design Team / April 31st '09	Assembly/Disassembly has been simplified to only bolts, with no compression or slip fittings.	4	3	3	36
Should be adapted to the current vehicle design with minimal modification	Existing vehicle dynamics have already been engineered and should be kept where possible to prevent further engineering challenges	Costly modifications to a design that has already been completed. Further engineering to components who have already been produced and proven as functional.	3	No use of DFM or DFA in initial design process	1	No modification performed to existing structure	1	3	Currently no modification to the vehicle has been performed.	Design Team / April 31st '09	Modifications have been performed to the existing vehicle structure, however a cloned version of the hub bracket has been implemented in order not to repeat previous engineering attempts that have been proven.	3	10	6	180
Allow for current wheels to mount without clearance issues	Wheels should not interfere with any components, and should be mounted with the current wheels offset	Wheels which cannot be mounted to hub. Wheels that must be mounted backwards may cause for safety related wheel issues (bent broken rim)	6	Structure/device created for mounting hub to suspension to large causing wheel interference issues.	10	Wheels are currently mounted backwards to avoid interference issues.	10	600	Hub mounts should chamfered to allow for wheel fitment, or redesigned to a smaller diameter.	Design Team / April 31st '09	Existing hub mounts have been removed and wheels will be able to be mounted in the proper position.	6	1	1	6

4.4 Calculation of Rigidity Index

The Rigidity Index is a calculation the design will be subjected to that will determine the relationship of the individual design parameters and to what degree they have an effect on each other. The overall relationship of the effects of all the design parameters will allow the Rigidity Index to be calculated and for an understanding of how flexible the design can be according to which variables remain fixed or unfixed. To quantify the Rigidity Index, all the parameters will be listed and described for a better understanding of how they relate to the design, then a table will be produced to show the relationships between the parameters.

4.5 Design Parameters

Several design parameter relationships will be compared to show a referenced relationship between them that can be quantified.

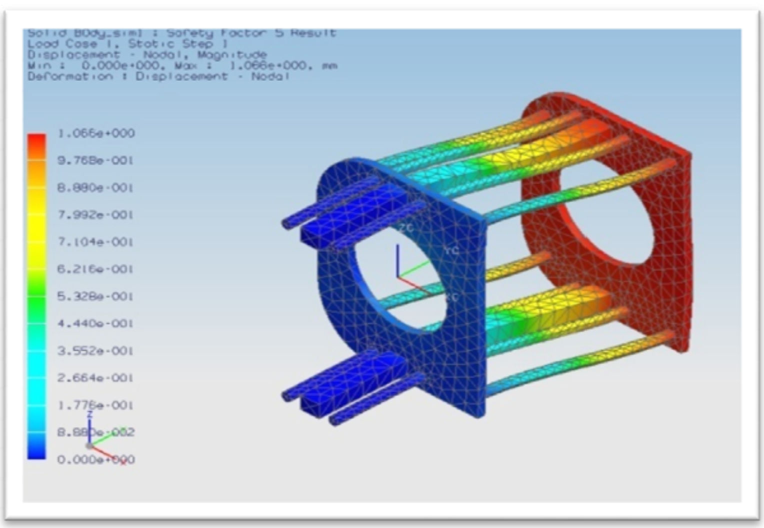


Figure 4.7 - Finite Element Analysis - NX4

The design parameters that will be compared are the following: (a) Mass: Mass of all components attributing to overall vehicle mass. Measured in [kg] or [lbs]; (b) Volume –

Space constraints: Overall space encompassing of system developed. Example: Storage of fuel effects range. Volume effects on storage pressure. Higher pressure = smaller volume for same range; and (c) Robustness/Safety Factor: Calculated with the assistance of CAD/CAM software suites such as Visual Nastran, COSMOSMotion/Works (Figure 4.7).

4.6 Interactions between Parameters

By studying the interaction of the parameters and how they affect each other, decisions can be made on which parameters need to remain constant and which can be flexible in the design process. The identifying of parameters relationships is a critical step towards minimizing the Rigidity Index in a design. Also, some parameters that are required to be fixed because of design constraints may also contribute to a system's over all rigidity.

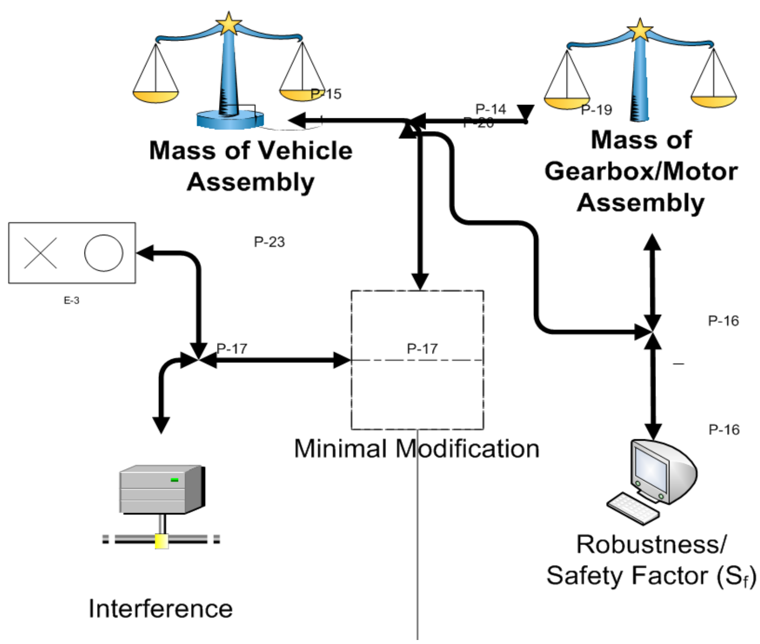


Figure 4.8 - Relationship of Design Parameters

In Figure 4.8 a basic pictorial is given as a mind map to depict the relationships between key parameters in the design of the hub and motor support assembly. It shows that by modifying the existing suspension of the dune buggy that can be affected by both the mass of the vehicle assembly and the mass of the gearbox/motor assembly. This key point is the drive for improvement on the second design iteration of the motor/gearbox assembly. In addition to several interference factors related to installation of the current assembly, which also can be solved by modifications to the OEM structure of the buggy itself.

4.7 Fixing One Parameter - Constraints for Others

Fixed variables will need to be identified as the initial step in order to determine how they will constrain other design variables. All parameters which are critical and must remain static should be fixed and be the main constraints of the design. These constrained parameters would be listed as fixed and cannot be changed. Ultimately, the fixed constraints would have the effect on the variable parameters.

An example of how this process would take place is if the Mass is fixed the following are affected:

1. *Material* Selection →Aluminum frame → Space Frame vs. Solid construction → *Robustness/ Safety Factor*
2. Power (to achieve set Power/Weight Ratio) → Motor selection →Define *Control* for associated power output

4.8 Rigidity Index:

To formulate a quantitative value for R_i = Rigidity Index, it is composed of parameters in the set design. R_i would be all of subset P ={p1, p2, p3, …,pn} where n parameters, p1 to pn are called the design parameters in the selected design process. For purpose of this design problem the parameters are as follows:

P = (W, Ro, WR, MM, Su, I) where; W is weight of assembly including all components, Ro is the robustness of the design, WR is the reduction o the vehicle weight, MM is the amount of modifications made to the existing vehicle, Su is the efficiency of space use, and I is the amount of interference caused due to the nature of the new design.

A common sense approach was taken using the knowledge of subject matter experts to choose values of how the different design parameters relate to one another. The relationship matrix shows how each parameter is related to each other and gives an overall idea of how flexible the design is as a whole comprising of the parameters listed.

Table 4.5 - Interaction Between Parameters Relationship Matrix

		Weight of Motor/Gearbox Assembly	Support /Robust	Reduction of Vehicle weight	Min. Mod.	Use of Space	Interfer.	Rigidity Index
1	Weight of Motor/Gearbox Assembly	1	5	6	5	2	1	20
2	Support /Robustness	5	1	5	4	2	1	18
3	Reduction of Vehicle weight	6	5	1	6	2	3	23
4	Minimal Modification	5	4	6	1	1	4	21
5	Use of Space	2	2	2	1	1	4	12
6	Interference	1	1	3	4	4	1	14
	Relationship Scale	1-6					Rigidity Index	108

1-No Relationship

6-Strong Relationship

4.9 Pugh Generation-Selection matrix

Each concept is evaluated relative to the current design which was presented in Section 4.2 which is the baseline system for comparison. If a concept is better than the datum it receives a "+". If a concept is the same as the datum it receives a "0". If a concept is worse than the datum it receives a "-". The total sum of all "+", "0", and "-" are used to determine the top five concepts for further evaluation.

During the first concept screening matrix the 90° Vertical design was processed. The motor casement, "C" channel bracket style, slide channel bars were then rated against the datum of the design illustrated in Figure 4.6. The screening matrix yields the "C" channel design concept as the #1 choice to continue evaluation.

Table 4.6 - Concept Screening Matrix

	Concepts				
Criteria	90° Vertical	Motor Case	"C" Channel Bracket	Slide Channel Bars	Current Design
1 - Weight	+	-	+	+	Datum
2 – Support /Robustness	-	+	+	-	
3 – Reduction of Vehicle weight	0	+	+	0	
4 – Minimal Modification	0	-	-	0	
5-Use of Space	+	+	+	0	
6 – Interference	-	+	+	0	
Sum +'s	2	4	5	1	-
Sum 0's	2	0	0	4	-
Sum -'s	2	2	1	1	-
Net Score	0	2	4	0	-
Rank	3*	2	1	3*	-
Continue?	NO	NO	YES	NO	-

The concept scoring matrix is then used to grade the concepts selected with their intended design parameters. The design parameters are weighted in accordance to their importance and then rated to give a final score which is tallied. In Table 4.6 - Concept Screening Matrix the “C” channel bracket receives the highest score and confirms what the selection matrix output was in Table 4.6 - Concept Screening Matrix

Table 4.7 - Concept Scoring Matrix

		Concept									
		90° Vertical		Motor Case		“C” Channel Bracket		Slide Channel Bars		Current Design	
Selection Criteria	Wt.	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score
1 - Weight	20%	5	1	3	0.6	5	1	4	0.8	4	0.8
2 – Support /Robustness	20%	3	0.6	4	0.8	4	0.8	2	0.4	2	0.4
3 – Reduction of Vehicle weight	15%	0	0	4	0.6	4	0.6	0	0	0	0
4 – Minimal Modification	10%	3	0.3	2	0.2	2	0.2	5	0.5	5	0.5
5-Use of Space	15%	5	0.75	4	0.6	4	0.6	4	0.6	4	0.6
6 – Interference	20%	2	0.4	3	0.6	5	1	3	0.6	3	0.6
	Total	3.05		3.4		4.2		2.9		2.9	
	Rank	3		2		1		4		4	
	Cont. ?	NO		NO		YES		NO		NO	

4.10 TRIZ-based Problem Definition

TRIZ’s design methodology was used to help in the process of ensuring that all possible design solutions had been thought of, and all aspects of those designs had been analyzed. This methodology engaged further brainstorming on possible solutions and modifications to solutions already created to ensure all avenues of design were covered. This exercise utilized TRIZ’s 39 design parameters and 40 Inventive principles. The 39 design parameters were studied and compared with the objectives of the design intent. An attempt was made to relate the design objective with all 39 design parameters as can be seen in Appendix I. A similar process was used with the 40 Inventive Principles (see Appendix J). The entire design was subjected through all 40 principles to determine if anything was overlooked or could be improved through the use of the principles.

From the 40 inventive principles the following were used to select design elements that would be implemented into the final design iteration.

- Make an Object Easy to Disassemble
- Bolts instead of welds, easily accessible
- Taking Out
- Remove unnecessary vehicle components
- Merging
- Merge bearings, transition power devices
- Nested Doll
- Place hub bearing into gearbox assembly
- Anti-Weight – merge
    - By performing the principles “Taking Out” and “Remove unnecessary vehicle components”
- Copying
- Use existing vehicle suspension design
- Colour Changes
- Transparency – Add Transparent covers to electrical devices

4.11 Minimizing the Rigidity Index

By sorting parameters from lowest interaction amongst other parameters to highest interaction we have:

Table 4.8 - Rigidity Index Parameter Relationship Matrix

		Weight	Support /Robust	Vehicle Suspension weight	Min. Mod.	Use of Space	Interfer	Rigidity Index
3	Vehicle Suspension weight	6	5	1	6	2	3	23
4	Minimal Modification	5	4	6	1	1	4	21
1	Weight	1	5	6	5	2	1	20
2	Support /Robustness	5	1	5	4	2	1	18
6	Interference	1	1	3	4	4	1	14
5	Use of Space	2	2	2	1	1	4	12
							Rigidity Index	108

Thus, we can now choose which parameters to fix, and which can remain flexible in our design in order to minimize the Rigidity. The minimization procedure would fix the following parameters: Reduction of vehicle weight, Minimal modification to the existing design of the vehicle, and the overall weight. Remaining parameters would be free constraints: Robustness, Interference and use of space.

Calculating the minimized Rigidity Index Yields:

$$\mathbf{R_i} = (23+21+20)/(18+14+12) = 1.45 \qquad (4.1)$$

4.12 Axiomatic Design

To study the sensitivity of the design, the axiomatic design methodology was used in order to compare functional requirements (FR) with design parameters (DP) [41]. This comparison will allow for a full understanding of how coupled or uncoupled the design is in its current state and will offer an outlook on where to decouple functional requirements. By using the axiomatic design process vulnerabilities can be detected in the early concept stage. Such violations would also be in direct violation of design guidelines or axioms. Since the current design also has a prototype, operational vulnerabilities can be studied to get a sense of the lack of robustness in the design at the operational level.

There are two axioms that the axiomatic design methodology follows [41]:

Axiom 1: The independence axiom- Maintain the independence of the functional requirements.

Axiom 2: The information axiom- Minimize the information content in a design.

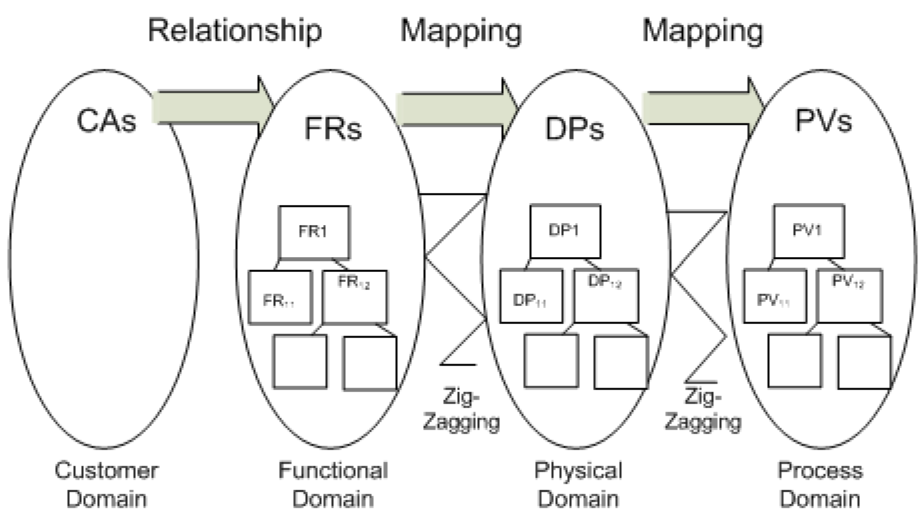


Figure 4.9 - Relationship between Domains [adopted from ref. 31]

A design map in the form of a sensitivity matrix will be formed to display how the realms of the functional domain relate to the physical domain as seen in Figure 4.9. The ultimate goal of design mapping is to facilitate design detailing when the mathematical relationships are identified in the form of transfer functions. Design mapping is required for Functional Analysis and Physical Synthesis. However for the purpose of this project, Axiomatic design will be used to identify sensitivities in the design between the physical and functional domains.

The sensitivity matrix lists all functional requirements on the left hand column, and the design parameters along the top row. Within the heart of the matrix exists values which determine the degree of sensitivity between the FR's and the DP's. In Table 4.9 four FR's are listed against four DP's, several coupling issues are present. By combining the parameters of weight into a single parameter several coupling issues are resolved as can be seen by the reordered sensitivity matrix in Table 4.10.

Table 4.9 - Sensitivity Matrix - Functional Requirements vs Design Parameters

Functional Requirements (FR) \ Design Parameters (DP)	Weight of Hub/Motor Assembly	Weight of Suspension Assembly	Material of Assembly	Method of Fastening
Mount Gearbox and Motor to Hub				A_{14}
Allow for ease of assembly disassembly				A_{14}
Dampening due to unsprung mass should remain unchanged	A_{31}	A_{32}	A_{33}	
Remove redundant bearing surfaces		A_{42}		

Table 4.10 - Sensitivity Matrix - Design Parameters combined

Functional Requirements (FR) \ Design Parameters (DP)	Method of Fastening	Material of Assembly	Weight of Entire Suspension Motor Assembly
Mount Gearbox and Motor to Hub	A_{11}		
Allow for ease of assembly disassembly	A_{21}		
Dampening due to unsprung mass should remain unchanged		A_{32}	A_{34}
Remove redundant bearing surfaces			A_{43}

4.13 Testing and Validation

Testing of the design will be done by strict real world testing. Various terrains will be investigated and time trials will be taking for traditional track exercises such as figure 8's, and slalom events. These metrics will then be compared to the OEM specs of the dune buggy which were recorded before all modifications. As well the current designs metrics will be tested and recorded to compare to future design iterations.

4.14 Electric Architecture

4.14.1 Component Selection – Controllers

In order to achieve full independent control of both motors on the rear wheel drive setup dual controllers would be needed to allow for complete control of both motors at the same time. A suitable controller for the permanent magnet motor had to be selected from an extensive list. (Table 4.11) Specifications of the controller will have to match the permanent magnet ETEK-R motor discussed in Section 4.1.

Table 4.11 - PM Motor Controller Comparison

Controller Comparison											
	Cost	Volts DC	Current Limiting	Torque Control	Max Current	Closed Loop Control	Thermal Protection	Battery Protect	Mass (lbs)	Progr.	Reg-en.
Kelly KD72401	438	24-72	Yes	Yes	400	Armature Current	Yes	Yes	8	Limi	Yes
Alltrax AXE4845	495	24-48	No	No	400	Armature Current	Yes	Yes	5.5	Yes	NO
Naitas TSP400-48	245	36-48	Yes	No	400	Armature Current	Yes	No	N/L	No	NO
Millipak 4 Quadrant	452	24-48	Yes	Yes	325	Armature Current	Yes	Yes	6.5	Limi	Yes
Robeteq AX2850HE	700	40	Yes	No	120Ax2	Encoder/ Tach	Yes	Yes	3.3	Yes	Yes

The controller will have to meet or limit the maximum current requirements of the motor, and will have to maintain a set supply of current for various durations (400 [A] peak). These set durations would resemble normal driving scenarios such as short bursts (10 [sec]) of power needed during brief acceleration periods, or moderate power during cruising.

In addition, stalled motor scenarios were considered and analyzed to ensure protection is accommodated when over current situations are met. When a DC permanent magnet motor is stalled, and the armature is locked, the armature current spikes. The controller along with other means such as inline quick blow fuses will have to monitor and limit current draw to protect the system from these types of situations. The stalled condition mimics that of a short and can be described by the following:

$$I_{max} = V_{battery}/R_t \tag{4.2}$$

A regenerative braking circuit built into the controller is a must in today's EV marketplace. The process of using the permanent magnet motors as generators while slowing the vehicle is the ultimate means to recoup energy lost while braking a vehicle. Such a circuit, situated within a controller, monitors for a brake-on condition and allows for the motor to act as a generator and feed its counter EMF back to the batteries in a controlled fashion. Controllers may also possess such features as variable regenerative braking where regeneration can be customized according to driving conditions or magnitude of braking.

Since a controller feeds a motor the necessary power to operate, a battery protection circuit or associated logic is necessary in order to prevent under charge conditions for the battery array. This protection must also be able to detect overcharge conditions in the case of regeneration. A battery protection circuit would monitor the battery state of charge and either cut power to the motors if an under charge state is dedicated or disable regeneration if an over charge state is detected. Additional characteristics necessary in a modern day controller would include MOSFET technology, analog resistive throttle input, closed loop control (encoder/tachometer).

The Kelly KD72401 permanent magnet controller offers all the specifications and options needed in order to power the ETEK-R motors and allow for seamless transition into the microcontroller logic system. It offers a peak of 400 [A] to allow the motors plenty of current to operate as well the voltage range spans from 24 to 72 [V] allowing for possible increases in power levels if needed during the experimental and testing stage of research. The standard options include: current limiting, thermal protection and battery level protection (in which nearly all the controllers offer). To allow for a simple installation the entire system is managed through a simple Windows based graphical user interface.

Table 4.12 - Motor Comparison

	Cost (USD)	Volts DC	Speed Max (rpm)	Cont. Current (A)	Current Max (A)	Output Max (hp)	Torque Max (Nm)	Weight (kg)	Power: Weight (hp: kg)	Cost: Power (USD: HP)	Eff. (%)	Style
ETEK-R	525	12-48	3700	100	330	15	42.9	13.6	1.1	35.0	91	Brushed DC
ETEK-RT	575	24-72	2400	150	330	18	52.8	12.7	1.4	31.9	91	Brushed DC
MARS PMAC	480	24-48	3500	100	300	15	42	10.0	1.5	32.0	90	Brushless AC
Lemco 200	1650	12-60	4000	100	400	21	60	10.7	2.0	78.6	91	Brushed DC
Lemco 170	1425	12-48	3264	140	300	16	33	8.5	1.9	89.1	88	Brushed DC
Lemco 130	1249	12-36	5400	75	100	5.3		3.0	1.8	235.7	88	Brushed DC
Hub Motors												
Csiro Solar Car	18,200	150	2865	N/R	N/R	2.4	50.2	10.9	0.2	7583.3	97	Brushless PM-DC
Flight-link HPD30	~17,000	400	2000	N/R	N/R	54	350	18	3.0	314.8	N/R	Brushless PM - AC
Flight-link HPD40	~30,000	400	2000	N/R	N/R	160	750	25	6.4	187.5	N/R	Brushless PM-AC

4.14.2 Component Selection – Motors

The choice of a suitable motor is critical in propelling a vehicle. Characteristics such as high torque coupled with a moderate top end RPM are crucial for suitable vehicle performance. A feasibility study was performed on the current motor types, along with the financials to have them implemented into a production style vehicle. A design parameter set for the vehicle were to allow it to accelerate to its top speed 100 [km/h] in fewer than 7 [s]. As well complexity in controls was another factor considered. Since the electronic rear differential would be in early development it would be needed for the controllers to be able to communicate with a central microcontroller in order to receive proper throttle inputs to modulate speeds of the rear wheels during turning manoeuvres. This required an interface between the motor controllers capable of allowing the motors to operate independently.

Hub motors must have high power and must be contained within the diameter of a vehicles wheel. Today's electric motors are on the brink of reaching these new standards of high power low volume packaging. Although hub motors have not reached main stream mass production, a few companies have emerged with sparse and expensive options for outfitting a vehicle with a hub motor. In consideration of the overall cost needed to accomplish this type of research project, a near wheel motor solution will be used to simulate the behaviour of a hub motor. To construct a vehicle for further research and testing, utilizing state of the art hub motors that have not reached the public market, was not feasible for this prototype. The costs as outlined in Table 4.12 and availability for hub motors to academia are nearly nonexistent. A near wheel motor approach was adopted to simulate a hub motor setup. A true hub motor has an RPM range between 0-2000 [rpm] for usable top-end speed of 143 [km/hr] on a 15” tire.

Table 4.12 illustrates the available motors that combine both the power needed to propel a light duty vehicle as well as encompassing that power into the confines of a near-wheel packaging. Table 4.12 also includes specifications for actual hub based motors, although their costs are extremely high due to their technologically advanced design and limited availability they have been included as a comparison to a pancake style motor which can be used to simulate a hub motor design. The table concludes with two ratios: a power-to -weight ratio, and a cost-to-power ratio. These are both important when choosing a motor for a mass production environment, or in this case, a budgeted research project. Hub motors, originally developed by Flightlink, have a very high power-to-weight ratio ranging from 3-6.5 [HP/kg], which exhibit an extremely dense ratio of power-to-weight.

The Csiro motor however has been capped in power due to the Solar Car competition regulations and concentrates more on overall efficiency peaking at 97.4%. The cost—ranging from $17,000-$35,000 USD each-of the hub motors is the major deterring factor from utilizing it. The estimated cost per horsepower is $187-$7583, and so the benefits of power-to-weight ratio simply cannot be justified this early in the design cycle when overall power-weight-cost ratios are considered. Nonetheless, the ability to fit a vehicle with these types of motors is costly.

The pancake style motors range from 1.1-3.0 [HP/kg], about a 1/3 that of the actual hub motors, however their cost-to-power ratios are substantially less at $35-$85 per horsepower. The pancake style motor that was chosen for the simulation build was the ETEK-R motor. The decision to use this motor was based on its low cost-to-power ratio, as well as its ability to be used with flexible, readily available and easy to configure permanent magnet DC controllers. Their affordable cost and dense power make these motors the perfect choice to simulate a hub motor system in a near wheel configuration.

The selection of the ETEK-R motor with a maximum speed of 3700 [rpm] at 48 [V] and coupling them with the 22" diameter off road mud tires give two unique challenges to the design. A direct drive setup with the ETEK-R would yield astronomical speeds of 390 [km/h] which is unpractical and out of the scope of the design project. The solution was to add an additional inline planetary gearbox with a high efficiency. The ETEK-R motor coupled with a 4:1 planetary gearbox (discussed in section 4.14.3) allowed for speeds of up to 97 [km/h], as well adding a multiplier for torque for dead stop starts.

The ETEK-R has very smooth torque curves and is able to produce its peak torque at nearly 0 [rpm], the power versus voltage curve (Section Chapter 1E) was evaluated to ensure the motor had a flat torque curve across its entire RPM band. In a similar fashion, its dimensions were noted to ensure fitment in the confined space of the outer corners of the vehicle, engineering documentation (see Appendix D) was used to create a CAD model so that interference verification could be performed before purchasing or committing to a certain product.

4.14.3 Component Selection – Gearbox

A majority of the motors that were available did not provide RPM's slow enough to propel a vehicle at reasonable speeds. The design parameter for top speed was capped at 100 [km/h] as the dune buggy in its factory form had a top speed of 80 [km/h]. Having chosen the ETEK-R as the motor moving forward a simple Excel spreadsheet calculator (Table 4.13) was created and used to determine optimal motor speeds and equivalent wheel speeds. The user can input maximum motor speed, the wheel diameter of the propelled wheel and an optional gear ratio. The calculator will then calculate the vehicle speed or wheel speed in both [km/h] and [MPH]. It was determined using this tool that with the ETEK-R spinning at a maximum of 3700 [rpm] that the vehicle would move 97.43 [km/h] (60.54 [MPH]) with a 4:1 gear reduction.

Table 4.13 - Excel Wheel Speed vs Motor Speed Calculator

Wheel Speed vs Motor Speed Calculator	
	Inputs
Motor Speed (Input RPM)	3700
Wheel Diameter (Input Inches)	22
Gear Ratio (Input 1: __)	4
Vehicle Speed (MPH)	60.54111
Vehicle Speed (Km/h)	97.43147

Since overall mechanical efficiency is the overall purpose of converting the vehicle to a near wheel direct drive setup a super efficient gearbox is needed in order to reduce the speed of the motor. In addition a compact unit was needed in order to maximize the space available for the motor and gearbox assembly. A planetary gearbox was selected by a company called Neugart USA, manufactured in Germany (Detailed specifications in Section Chapter 1G). The gearbox was custom made to suit the flange of the ETEK-R motor and was able to be ordered in the desired 4:1 operating ratio. The gearbox operates at 96% efficiency and has virtually no backlash when compared to conventional gearboxes. It also has a 3300 [N] axial load factor which would be sufficient for supporting the entire vehicle and removing the wheel bearing assembly in its entirety.

4.14.4 Rear Electronic Differential

The prototype that has been developed allows for a revolutionary style of independent drive. Currently, mechanical transfer devices incorporating differentials, viscous couplings, and limited slip setups utilize electrical subsystems to apply logic to the systems to allow them to become responsive to driving conditions. Despite the advancements made with these mechanical devices, the limitations stem from their mechatronic systems and complexity. The hub motor arrangement changes the limitations of logic controlled systems.

In order to achieve true independence of control for both motors on the rear wheel setup a mirrored electronics system was needed. This mirrored system would allow for feedback to be sent back and forth from one channel to the other to allow for completely independent control. As explained earlier a microcontroller would be used for this feedback as well as a means of monitoring the entire system (Figure 4.10). Input devices such as throttle, brake, forward reverse selector, steering are inputted through the microcontroller in order to be processed to determine the overall status of the vehicles controls.

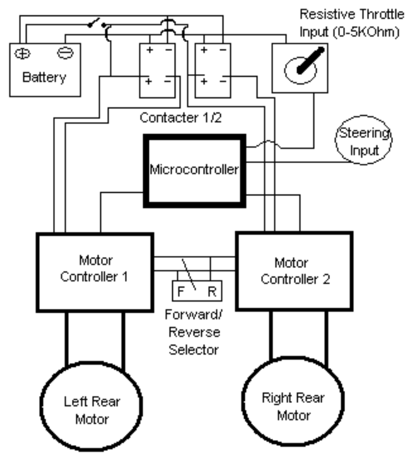


Figure 4.10 - Rear Drive Hub Motor Schematic

The differential setup consists of two independently controlled hub motors, controlled by electronic speed controllers. The input of the throttle as well as the input of the steering angle is communicated by wire to a microcontroller setup. An algorithm was created in order to compute desired turning angle to outboard wheel speeds. [45]

The steering input to the microcontroller consists of two potentiometers mounted on either side of the wheel in a gear setup. Two potentiometers were used to allow for the use of the linear portion of a potentiometers range; one for a left turn and one for a right turn. The resistance given by the potentiometers is then processed and converted into the desired steering angle. For the purpose of experimentation two separate algorithms have been formulated into code to compare the results when real world testing begins. The first code is composed of Ackerman's formulae [46]:

$$\delta = \frac{\delta_{\mathrm{in}} + \delta_{\mathrm{out}}}{2} \tag{4.3}$$

$$\omega_{in} = \frac{V}{r}\left(1 - \frac{d\tan(\delta)}{2L}\right) \tag{4.4}$$

$$\omega_{out} = \frac{V}{r}\left(1 - \frac{dtan(\delta)}{2L}\right)$$

(4.5)

With Ackerman's formula the difference in angle of the inner and outer wheel are taken into consideration. In the following formula only inner and outer wheel speeds are considered with no compensation to the difference in angles on the front steering wheels:

$$v_{diff} = \frac{V_o}{v_{avg}} = \frac{R - r}{R_{avg}} = \frac{t}{R_{avg}}$$

(4.6)

Equation (4.5) shows the approximation of the dimensionless velocity differential between the outside and the inside wheels. This formula will be programmed with the necessary static parameters such as vehicle track in order to calculate properly defined independent wheels speeds which would then be outputted to the corresponding motor controllers.

Additional inputs are required in order to be able to fulfil the needs of the above algorithms. A throttle input is required to allow the operator full control on speed; a resistive throttle input is currently incorporated and has the ability to bypass the microcontroller setup and input directly to the motor controllers themselves.

Feedback from the motor/wheel assemblies are needed in order to determine wheel speed on both the left and right rear wheels. Currently, armature feedback is being used to calculate wheel speed through the motor controllers. This will not, however, be accurate enough for a proper assessment of wheel speed. Experimentation with optic and reflective sensors, mounted on the gearbox output shaft, are being performed to achieve a resolution of 1600 [checks/min].

Also, DC permanent magnet motors presently allow us to make several calculations based completely on the design characteristics of the magnet construction of the motors themselves. Torque can be calculated due to its dependency on armature current, and the flux stays relatively constant and torque can be described by Equation (4.6) [46].

$$Torque = K\ x\ \Phi\ x\ I_a \tag{4.7}$$

Torque and speed are greatly affected in slower speeds with the advancements in magnetizing force that are found in today's permanent magnet DC motors. This higher support for magnetism extends the linear characteristics for torque as well as speed down to the idle state of the motor. The magnetic force and its relation to the flux density of the motor are described by Rowland's law in Equation (4.7) [20].

$$B = Hu \tag{4.8}$$

From this we can further calculate the speed of the motor by knowing the motor's terminal voltage (Vt) with Equation (4.8):

$$S = (V_t - I_a\ R_a)/K\ \Phi \tag{4.9}$$

The efficiency of the motor is another critical design characteristic. The importance of efficiency in motor selection is twofold: the ability to transfer electrical energy to mechanical energy and the second being the opposite action, converting mechanical energy back to electrical energy in the aspect of regenerative braking. Efficiency can be measured in a motor with the relationship of its mechanical torque relative to the input of electrical power that is being supplied, Equation (4.9) [46].

$$Efficiency = (Torque_{out}\ X\ RPM)/((V_t\text{-}I_tR_t)/\ x\ I_t) \tag{4.10}$$

4.14.5 Component Schematic

The electrics of the vehicle were performed in a parallel manner to maintain complete separation in control between the two rear wheels. This was done in order to leave avenues for further development of stability and traction control systems open and to increase the level of flexibility in the design. Although the complexity of the electronics schematic increases (Figure 4.14) dramatically by maintaining independence between both motors, the rigidity of the design remains minimized for future developments. The system starts by delivering power from 32 Lithium Iron Phosphate cells which are wired in series to give a total of 48 [V] (Figure 4.14-2) of power at 200 [Ah], this power source is fused at 400 [A] (Figure 4.14-4-a) per controller which are also rated at 400 [A]. The power is then transferred through two separate main contactors (Figure 4.14-5-a) which are activated by a main power switch (Figure 4.14-3). The main contactors supply power to the reversing contactors (Figure 4.14-6-a) which change polarity according to the direction selected on the forward and reverse switch (Figure 4.14-10) located on the dash of the vehicle. Power flowing through the reversing contactors is controlled via the motor controllers which ultimately have full control on power output and can be programmed to limit current, ramp up speed and top speed. The controllers require inputs for the throttle and brake, these are provided via an electric by-wire-throttle (Figure 4.14-9) which consists of a spring returned 5K [Ohm] potentiometer and limit switch. The brake switch is also resistance based with a hard limit switch (Figure 4.14-8a) to show that the brake has been triggered. This switch is wired to a transmitter which wirelessly transmits the brake signal to a receiver (Figure 4.14-8b). This in turn sends the brake signal to the controllers to activate regenerative braking at the degree commanded by the operator.

The buggy runs on three separate power supplies. A main 12 [V] power distribution block (Figure 4.14-11) which allows for the original accessories of the buggy to operate such as headlights, turn signals and the horn. The 12 [V] supply is provided by a 48 to 12 [V] DC/DC converter (Figure 4.14-10). The second power distribution block is a 5 [V] signal provided by a DC/DC converter incorporated into the motor controllers. It feeds power to the receiver for the by-wireless brakes and to the microcontroller for the electronic differential (not pictured) as described in section 4.14.4. The third power supply is the 48 [V] supply direct from the batteries; all solenoids on contactors are powered through this supply as well as secondary power to the controllers. All three power distribution blocks are fused for all outputs with low current fuses. The main high current 48 [V] supply has a safety disconnect mounted beside the cockpit for the safety of the operator. The main safety disconnect will also cut supply to all three power sources.

A CAD layout (Figure 4.12) was performed to plan for and to allow for adequate space on the mounting platform that houses the batteries. A preliminary layout was performed with proper dimensioning and then duplicated with actual components in the buggy (Figure 4.11)

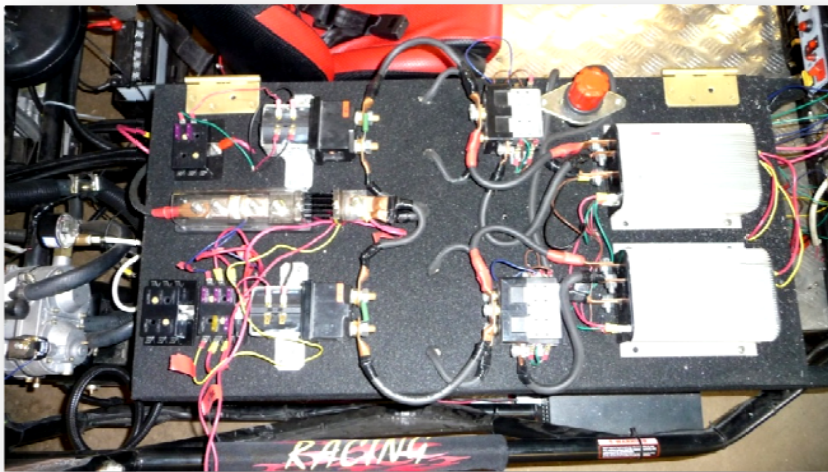


Figure 4.11 - Electronics Wiring Layout

The similarities between the virtual model and the CAD model can be seen between the two images. With the only differences being added distribution blocks that allow for each power feed to be properly fused. In addition, the emergency disconnect was moved closer to the operator for ergonomics and ease of use.

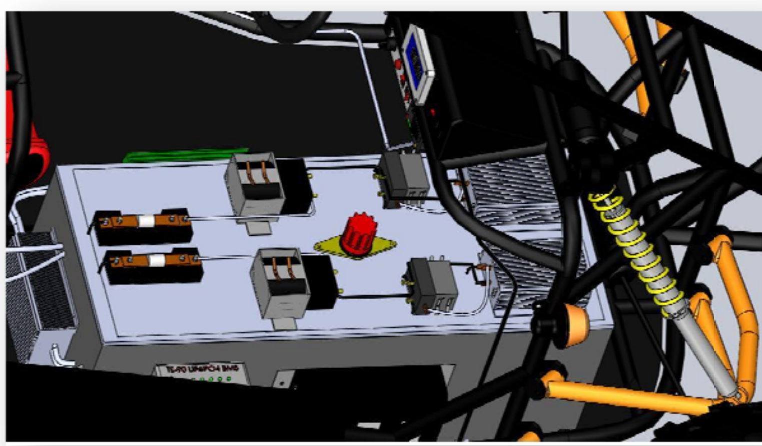


Figure 4.12 - CAD Layout of Electronics

A safety addition that was added to the design when reviewing all aspects through TRIZ was the addition of transparent plexiglass both to the top of the battery box electronics area, and on top of the batteries and battery terminals themselves. This eliminated any possibility that anyone could lean up against high voltage terminals and possible get electrocuted. While adding this safety feature, the E-stop was still made accessible by insetting the plexiglass around the e-stop knob (see Figure 4.13).

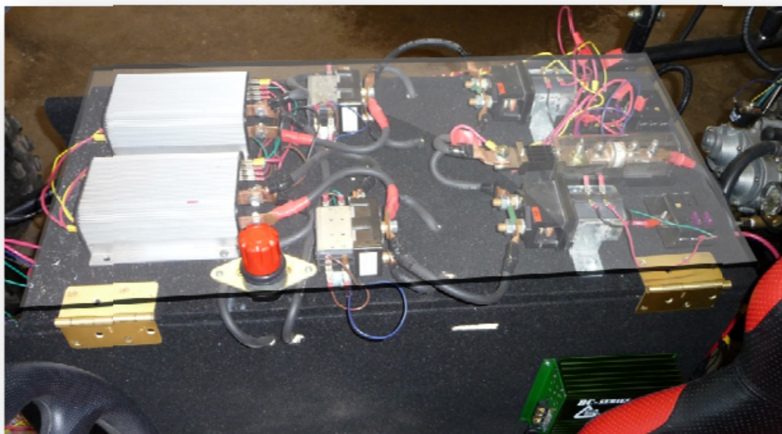


Figure 4.13 - Plexiglass Safety Cover Over Electronics

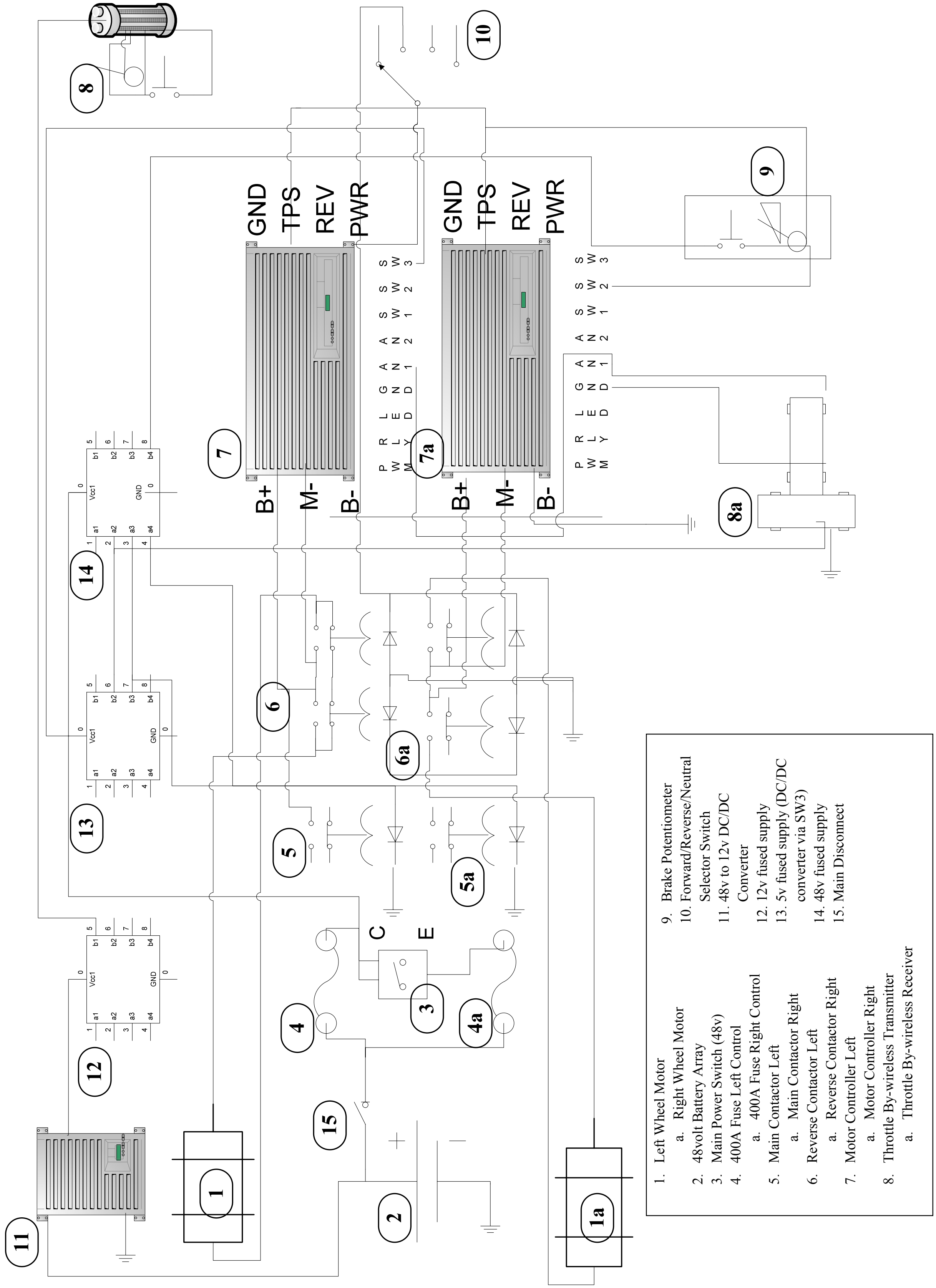


Figure 4.14 - Electrical Schematic Vehicle Controls

4.14.6 By-wire Throttle

The electric throttle which is inputted into the motor controllers to allow for user control of motor speeds is a spring tensioned potentiometer encased into a cast aluminum storage box (Figure 4.15). It was chosen for its similarity to today's conventional gas pedals. The dune buggies original gas pedal offered very little feel because of this it was not chosen to be adapted to by-wire capabilities. The by-wire throttle feeds the dual controllers with two separate signals, the first being a signal that throttle has been applied through a hard limit switch. Once throttle has been applied, regenerative braking is disabled and the controller looks for increased resistance as more throttle is applied. The controllers offer the ability to change the throttles response characteristics. The dead zone of the potentiometer can also be adjusted through the controllers GUI interface, as well as the sensitivity and rate of throttle applied. This enables the user to customize the vehicle to the 'feel' which is familiar to them. For testing purposes, it has also allowed for gradual throttle applications to ensure all systems were operating properly before aggressive throttle testing could occur.

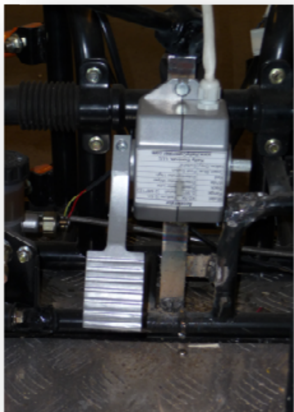


Figure 4.15 - By-wire throttle

4.14.7 By-wireless Brakes

The dune buggy test bed came with front and rear hydraulic disc brakes, commonly this style of brake is proportioned to 90% front brakes and 10% rear brakes. For the purpose of this study the rear hydraulic brakes were removed completely. All lines, callipers, mounting brackets and discs were discarded. The purpose of this would be to gauge whether or not rear regenerative brakes would allow the vehicle to stop sufficiently albeit only replacing approximately 10% of the total braking power. The innovativeness of this system comes in the transmission of the braking signal from the operator. The hydraulic brake pedal was kept, as the front brakes were still hydraulic disc, however a brake switch was added as well as a wireless analog brake trigger (Figure 4.16) to input total braking effort. The reason the brakes were used for the experimentation of by-wireless technologies as opposed to the throttle is because of the mechanical redundancies in the braking system. Although the rear brakes were completely removed, testing confirmed that the front brakes encompassed sufficiently braking power to safety stop the dune buggy. In addition the controllers and motors were suited for regenerative braking, which allowed for the electrification of the rear braking system through the use of the newly added permanent magnet DC motors. The solution naturally formed itself into a redundant control system, with the front brakes being mechanically driven, and being commanded from a mechanical braking linkage, and the rear brakes being controlled through electronic by-wireless means.

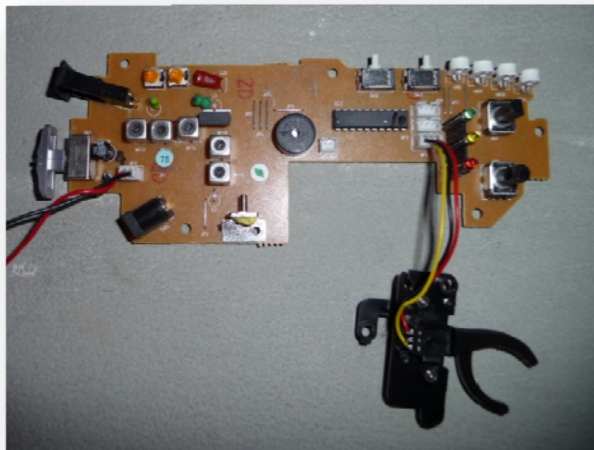


Figure 4.16 - Analog Brake Trigger and Transmitter

The analog brake trigger is connected to a wireless FM transmitter that sends the brake signal to a receiver which than communicates directly with a servo drive (Figure 4.17). The brake trigger is located directly at the brake pedal, and the receiver and servo based potentiometer is located with the electronics and motor controllers. The motor controllers receive the brake signal via a servo controlled potentiometer which moves with the corresponding input of the brake pedal. This system acts as a pulse width modulation to analog converter, with a mechatronic style solution. It allows for a visual reference on how much brake is being applied and if that signal is reaching the controllers. The solution offers the ability to display that there is in fact no mechanical linkages connecting the brake pedal to the rear brakes. The visual display also offers a sense of comfort that a visual reference is available to show braking response as direct visual feedback. The use of an FM transmitter is for experimental use only and by no means would be suitable for a licensed motor vehicle. This proof of concept is an attempt to display, test and study the opportunities of using by-wireless technology for functions such as rear brakes if deemed non-critical to the overall vehicles safety, or as a redundant backup to by-wired applications.

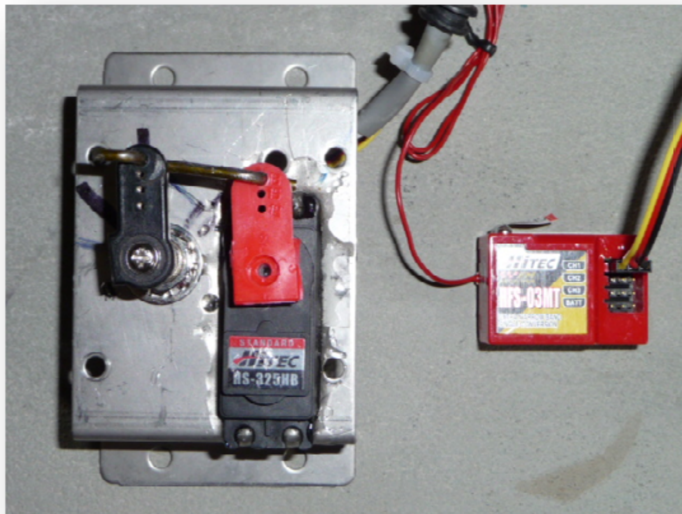


Figure 4.17 - Servo Controlled Potentiometer and Receiver

As the brake is applied the servo motor responds accordingly by moving the potentiometer in a smooth linear fashion sending a resistive signal between 0-5 [KOhms] to the controllers. Shown in Figure 4.18 is an example of how the servomotor responds to a brake signal varying from no brakes, to half application, to full brakes. Gauge overlays will be placed on the servo housing to better display braking levels. The motor controllers would then apply regeneration to the rear motors in the same varying degree according to the resistive input that it receives from the potentiometer. The motor controllers can also be programmed to increase the degree of regeneration, or stopping power to suit the operator or in this case to suit the lack of rear hydraulic brakes.

Although this is just a prototype, safety was a factor and was an influence in the design. There is a hardwired brake switch that needs to be switched in order for the regenerative braking system to be active through wireless control. This means that the brake pedal first needs to be applied physically for the switch to be made in order for the signal of the wireless brake control to be active.

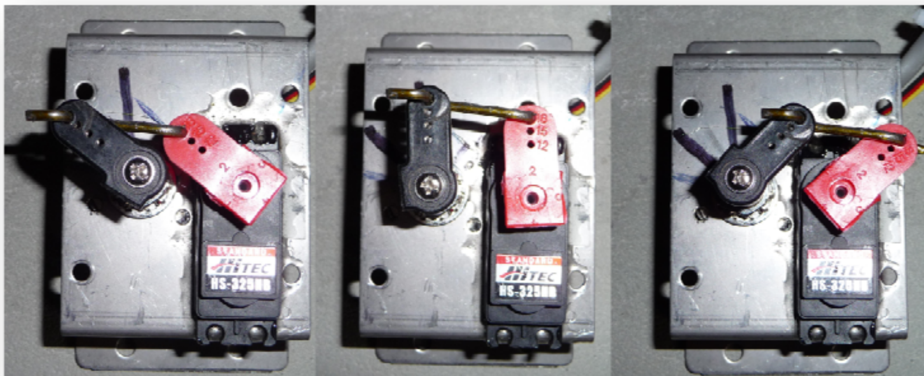


Figure 4.18 - Servo Controlled Potentiometer – No Brakes, 1/2 Pedal, Full Brakes

This prevents any possibility that a wireless signal could interfere with the operation and cause braking when not intended by the operator. Closed circuit testing was performed with only front brakes active on the dune buggy, and they posed to offer enough braking power for moderate to aggressive driving styles. In addition the electro-mechanical solution that was created allows for a visual of the amount of braking that is occurring by-wirelessly. The servo/potentiometer setup can be fitting with a gauge overlay and can display the current degree of braking.

Chapter 5 Results

After a methodical study on how the hub motor and gearbox assembly could be improved through the four design methodologies; FMEA, Rigidity Index, QFD and TRIZ it was clear to see that improvements were needed in the area of weight reduction to both the designed assembly and the vehicle suspension assembly as well as concentration to eliminate interferences the current design had with the vehicle structure. Although a prototype of the detailed redesign has not been produced a concept sketch (Figure 5.1) has been made to example the new design iteration. It incorporates a modified hub assembly trailering arm setup. The entire hub assembly has been removed with a new bearing plate mount. The bearing plate mount will bolt directly to the gearbox out sleeve housing.

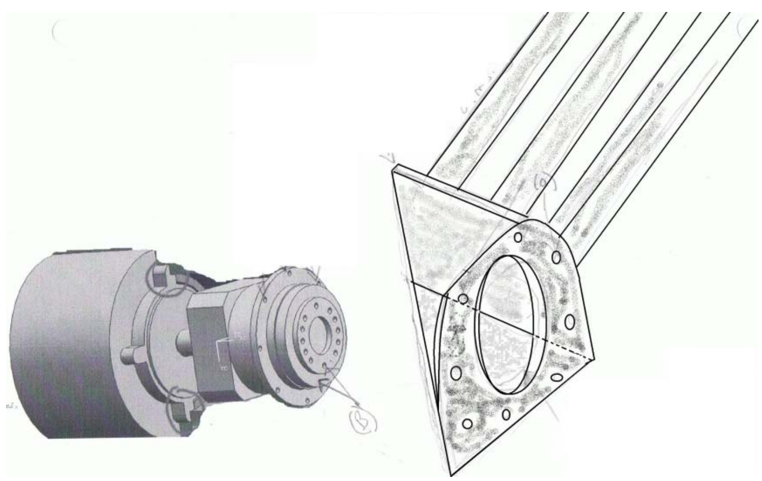


Figure 5.1 - Concept Sketch - Design Iteration #2

The concept sketch has evolved to the detailed design process in which a full CAD model (Figure 5.3) has been produced to show proof of concept and fitment details. The final design concept has modified the existing hub assembly of the dune buggy to allow for the removal of redundant mounting components. It should be noted that the original design iteration was handicapped by a design parameter which did not favour changes to the OEM structure of the dune buggy. Through the analysis performed in the early stages of the design it was shown that modification was necessary in order to optimize the functionality of the mounting device. This optimization can be seen by the lack of additional structure and as well in overall weight. The entire assembly has been reduced in weight by 2.4 [kg]. The original design weighed a total of 30.2 [kg] including the motor and gearbox, mounting structure and trailering arm.

Broken down the weight was as follows:

Table 5.1 - Weight Comparison - 2nd Design Iteration vs. 1st

Near Wheel Motor Mount Weight Breakdown (First Design Iteration)		Near Wheel Motor Mount Weight Breakdown (Second Design Iteration)	
Component	Weight (kg)	Component	Weight (kg)
Motor	13.6	Motor	13.6
Gearbox	7.0	Gearbox	7.0
Trailering Arm	3.8	Trailering Arm + Mount	7.2
Designed Mount	5.8		
Total Weight	30.2	Total Weight	27.8

The simplicity of the design and lack of additional and redundant components can be seen when comparing Figure 5.3 with the new design displaying the gearbox and motor assembly fully without additional supports and mounting brackets (Figure 5.2). Again, the addition of the added mounting brackets was intended to allow for minimal modification to the OEM dune buggy suspension design.

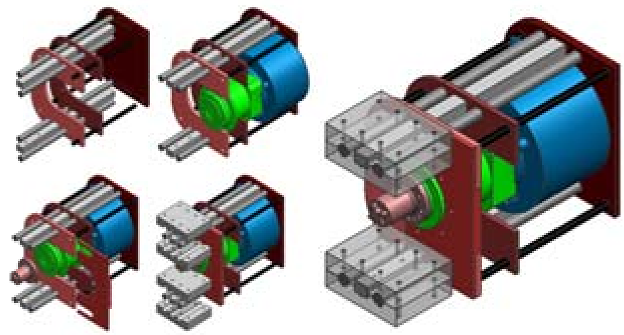


Figure 5.2- 1st Design Iteration - Mounts and Supports

The contrast between designs can be further displayed when comparing the virtual model of the new design in Figure 5.3 to the actual prototype in Figure 5.4. The inboard space constraints have been minimized and the gearbox and motors can be easily removed and installed.

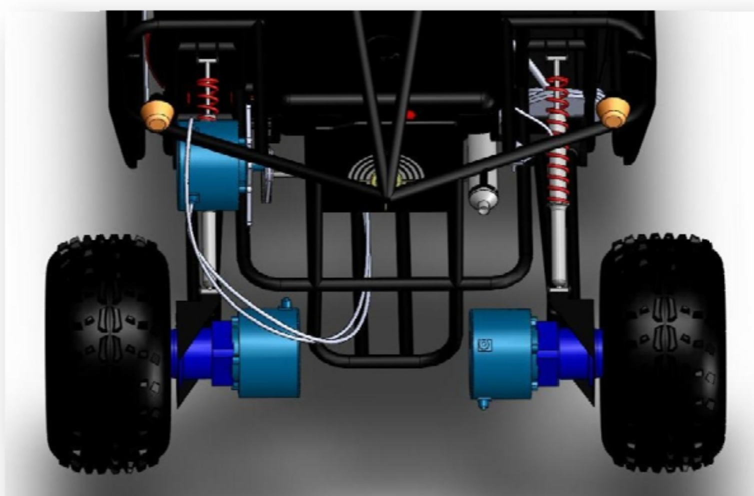


Figure 5.3 - Final Design - Motor Gearbox Mount

The mounting blocks on the first design have also been removed which allow for the proper offset of tire to be mounted on the buggy. In addition with the weight savings, handling and suspension response will be improved due to the decrease in unsprung weight.

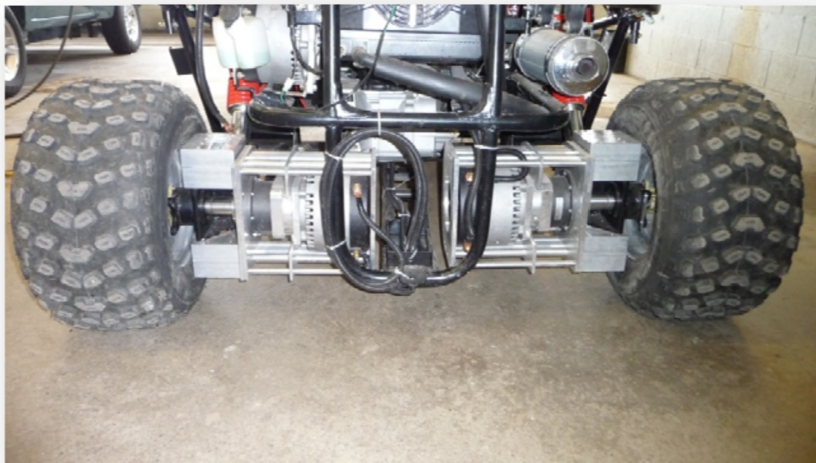


Figure 5.4 - 1st Design Iteration Prototype Manufactured and Assembled

Handling has been reduced due to the additional weight of the batteries and increased unsprung weight with the near wheel motors. This reduction in overall handling is very minimal however and could be minimized with upgraded suspension as the OEM struts and springs are currently being used on the buggy. The batteries additional weight causes the vehicle to want to under steer more during aggressive turns at moderate speed. The hub motors and gearboxes move freely with the entire suspension assembly and have not had any immediate side effects from the trial runs that they have been subjected to.

5.1. Testing and Performance Data

It was imperative to test the buggy after the modifications were completed. The data would be able to be compared to the benchmark testing of the original OEM dune buggy in which performance data was collected prior to modifications and removal and rebuild. The testing was performed to target three areas of performance: 1) Acceleration, 2) Loaded Regenerative Braking, 3) Unloaded Regenerative Braking and finally 4) Loaded Hydraulic and Regenerative Braking.

Acceleration tests were performed in a relatively level paved private parking lot. The test started from a standstill and the vehicle would accelerate from 0 to 60 [km/h] with a stop watch timing the event. Five separate trials were taken in each direction and then averaged to eliminate the effects of a slight grade in the parking lot or a consistent wind advantage. The testing was performed with a 100 [kg] driver in all instances. The results of the trials are seen in Table 5.2.

Table 5.2 - Acceleration Benchmark OEM Dune Buggy 0-60 [km/h]

Trial #	East Time [s]	West Time [s]	Avg. Time [s]
1	13.65	12.76	13.21
2	13.42	12.88	13.15
3	13.33	12.25	12.79
4	13.8	12.45	13.13
5	13.12	12.91	13.02
Average [s]	**13.46**	**12.65**	**13.06**

The dune buggy accelerated on average to 60 [km/h] in approximately 13 seconds flat. The results showed a slight biased in the westerly direction possibly due to a slight decline in the pavement that would allow for an increase in acceleration in that direction. The modified dune buggy was subjected to the same acceleration test from 0 to 60 [km/h]. The test was performed with a battery state of charge of 49 [V] and the same 100 [kg] driver.

Table 5.3 - Acceleration Hub Motor Conversion 0-60 [km/h]

Trial #	East Time [s]	West Time [s]	Avg. Time [s]
1	11.3	11.01	11.155
2	11.45	10.9	11.175
3	11.28	10.95	11.115
4	11.29	10.88	11.085
5	11.34	10.89	11.115
Average [s]	**11.332**	**10.926**	11.129

The dune buggy was able to show improved results when compared with the OEM setup as outlined in Table 5.3.

The dune buggy fitted with the two ETEK-R motors was able to outperform the OEM gasoline engine with a total averaged time of approximately 11.1 seconds. This test yielded nearly a full 2.0 second improvement in acceleration from 0 to 60 [km/h] (see Figure 5.5).

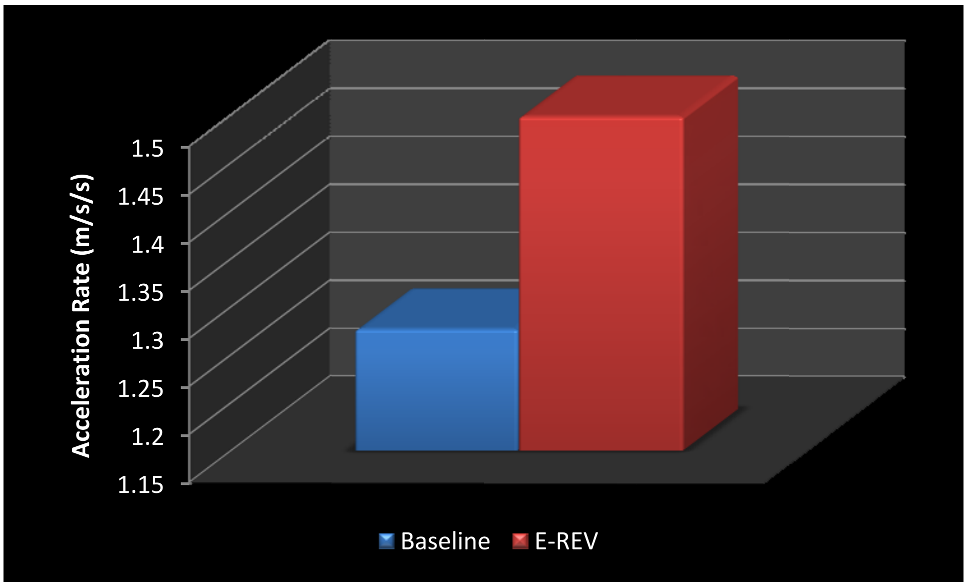


Figure 5.5 - Dune Buggy Acceleration Testing Summary

The regenerative braking system was also subjected to benchmark testing. The dune buggy was tested in its unmodified form for its braking performance.

Table 5.4 - OEM Braking Benchmark 40-0 [km/h]

Trial #	Stopping Distance [m]
1	12.0
2	11.3
3	14.7
4	10.0
5	14.0
Average	**12.4 [m] (40.7 [ft])**

The test consisted of accelerating the vehicle to 40 [km/h] and braking to a standstill. This was performed for a total of five times leaving five minutes of cool down between runs and averaged. The results are shown in Table 5.4.

The results from Table 5.4 show that the OEM dune buggy was able to stop on average from 40 [km/h] in 12.4 [m] or 40.7 [ft]. After the removal of the hydraulic rear brakes and the addition of two ETEK-R motors equipped with Kelly regenerative braking controls the braking was analyzed in several different tests. The tests for braking took into consideration the possibility of only braking with regenerative brakes, showing the capabilities of such brakes, as well as braking in unison with the front hydraulic braking system.

The first test consisted of disabling the front hydraulic brakes and braking utilizing the rear regenerative brakes at 50% total regenerative braking power. 50% of total regenerative braking power is a function of total current capability of the controllers themselves. Thus 50% of 400 [A] would yield a total braking current capable of 200 [A] per controller. The 50% regenerative brake test was conducted from 40 [km/h] to a standstill. The results were as shown in Table 5.5.

Table 5.5 - 50% Regenerative Braking 40-0 [km/h]

Trial #	Stopping Distance [m]
1	21.8
2	20.9
3	22.2
4	23.4
5	24.1
Average	**22.5 [m] (73.8 [ft])**

The vehicle was able to stop in an average of 22.5 [m] and it was noticed that the distance was increasing on each trial. This was thought to be the case due to increased heat into the system, including motors and brushes as well as the battery state of charge was approaching its maximum. An increase of 10.1 [m] (see Figure 5.6) was seen when compared to the OEM braking benchmark that was set in Table 5.4. This result was in line with what was expected with the front hydraulic brakes disabled and only 50% current enabled on the regenerative brakes.

The next test was to increase the regenerative braking from 50% to 100% full regenerative braking, while still disabling the front hydraulic brakes. This test would show the full potential of the rear regenerative brakes, with no hydraulic assist.

Table 5.6 - 100% Regenerative Braking 40-0 [km/h]

Trial #	Stopping Distance [m]
1	15.8
2	15.7
3	15.7
4	15.9
5	15.95
Average	**15.8 [m] (51.8 [ft])**

The rear ETEK-R motors was capable of stopping the vehicle in 15.8 [m]. When compared to the 12.4 [m] benchmark the regenerative braking system was outperformed by only 3.4 [m] (see Figure 5.6) with no hydraulic braking system active. This test shows that 78% of the braking could be performed by the regenerative braking system alone, with no hydraulic assistance from the front brakes.

The final on road braking test was performed with 100% regenerative braking enabled in the rear, and the front hydraulic brakes connected. The test was again performed from 40 [km/h] to a standstill. The results are as shown in Table 5.7.

Table 5.7 - 100% Regenerative Braking + Hydraulic Front Brakes 40-0 [km/h]

Trial #	Stopping Distance [m]
1	11.6
2	11.8
3	12
4	12.2
5	12.4
Average	**12.0 [m] (39.3 [ft])**

Stopping distance has improved from the OEM benchmark data. The OEM braking distance of 12.4 [m] was surpassed by 0.4 [m] for a total stopping distance of 12.0 [m] by utilizing the regenerative braking system instead of rear hydraulic brakes. Figure 5.6 displays a summary of all the load braking tests performed, displaying the improvement of braking systems and reduction of stopping distance from coasting to utilizing full braking power of both systems.

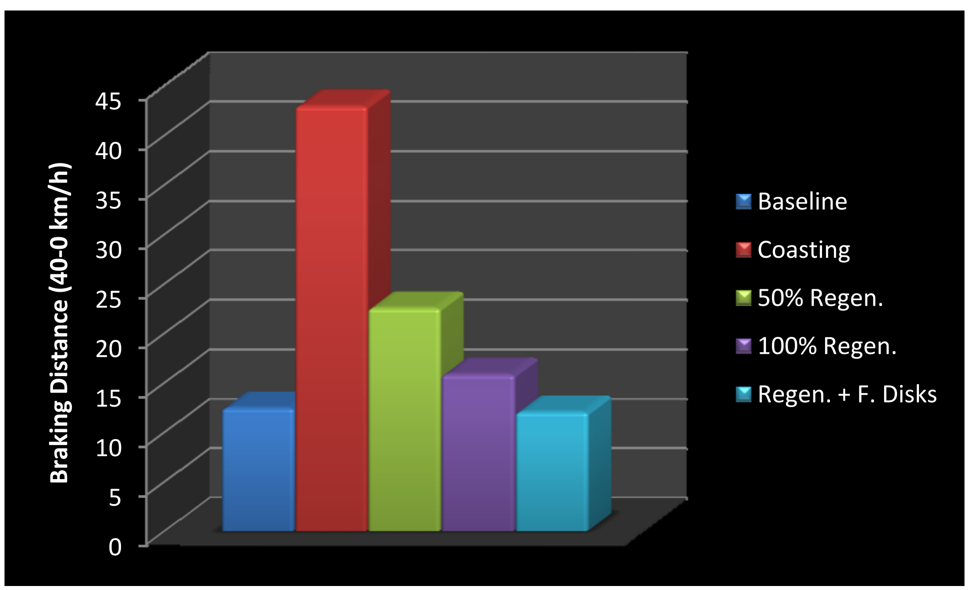


Figure 5.6 - Braking Test Summary 40-0[km/h]

To verify the results seen above a no load coasting test was performed. The vehicle was suspended with the rear wheels in the air, a full throttle run, with a wheel speed of 100 [km/h] was achieved. The wheels were allowed to coast to a stop with no braking applied. This would allow the effects to be seen that the permanent magnet motors would have on the free wheel spinning of the wheels. The results of the five trials and the average can be seen in Table 5.8.

Table 5.8 - No load Coasting Stop 100 [km/h]

Trial #	Stopping Time [s]
1	9.01
2	8.88
3	8.92
4	8.98
5	8.95
Average	**8.95 [s]**

The wheels were able to stop in 8.95 [s] on average with no braking power being supplied and no regenerative energy being harnessed. It can be assumed that a wheel and freewheeling bearing assembly that this time would have been significantly longer in duration and that the nature of the permanent magnet motors offered the resistance to slow the wheels in the time observed.

The experiment above was repeated with 50% regenerative braking applied from a wheel speed of 100 [km/h]. No other forms of braking were used as the rear hydraulics was removed during the conversion process to rear near-wheel motors. The results can be seen in Table 5.9.

Table 5.9 - No load 50% Regenerative Braking Stop 100 [km/h]

Trial #	Stopping Time [s]
1	4.51
2	4.48
3	4.5
4	4.49
5	4.5
Average	**4.5 [s]**

The results from the no load 50% braking test reinforced the findings in the load test. Braking from 100 [km/h] to a standstill was performed in 4.5[s]. This showed a 4.45 [s] improvement from the coasting freewheeling test which resulted in a stopping time of 8.95 [s]. The 4.45 [s] performance improvement can be correlated to a 50.2% decrease over the coasting to a stop testing experiment. When compared to the loaded experiment which yielded a 52.4% improvement in braking when coming to a standstill from 40 [km/h] (see Figure 5.7).

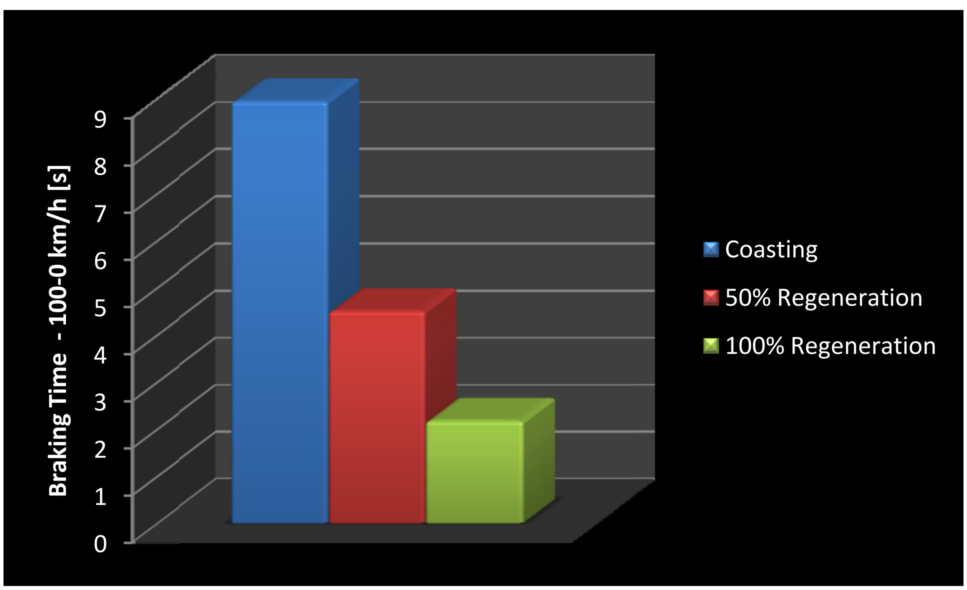


Figure 5.7 - No Load Regenerative Braking Summary

The test was repeated again with a 100% regenerative braking load applied. The test was performed to be able to test the full capability of the regenerative braking system as well as to compare the results with the 100% regenerative load testing. The results of the stopping times from 100 [km/h] to a standstill can be seen in Table 5.10.

Table 5.10 - No load 100% Regenerative Braking Stop 100 [km/h]

Trial #	Stopping Time [s]
1	2.15
2	2.18
3	2.14
4	2.2
5	2.17
Average	**2.17 [s]**

The regenerative braking system on the rear brakes was able to slow the unloaded rear wheels from a speed of 100 [km/h] to 0 [km/h] in an average time of 2.17 [s]. When compared to the 50% regenerative no load test, the 100% regenerative test showed a 48% improvement in time. Effectively reducing the time from 4.5 [s] to 2.17 [s], a total reduction of 2.33[s]. In contrast to the coasting down deceleration, a reduction of stopping time of 6.17[s] was observed. Reducing the stopping time from 8.95 [s] to 2.17 [s] yielded a 75% reduction in braking time when compared to the coasting experiment (see Figure 5.7).

5.2. Problems and Failures

The by-wire throttle functions have been tested with moderate driving levels. The responsiveness and feel is immediate and mimic that of a sporty performance vehicle.

This is partially due to the immediate torque that is available through the electric drivetrain and direct drive near wheel setup.

During testing it was seen that the by-wire throttle faults out the controllers occasionally with throttle levels above 50% and below 75%. The supplier for the Kelly throttle unit suspects a faulty potentiometer which is ‘glitching’ at the 70% throttle level. The throttle will be removed and returned to the manufacturer for replacement. The controller monitors movement in the throttles position and if it does not see a continuous movement it will throw a fault and shut the system down temporarily. The controller will then display the throttle fault through a series of blinking LED’s. The controllers then need to be reset to resume driving. This fault control has posed to be of vital importance in both safety and troubleshooting.

A near catastrophic failure occurred to one of the drive motors during initial bench testing of the motors. A slight ticking sound could be heard when the motor was rotated by hand, however when spun under power the ticking would no longer be audible. During the first test run of the vehicle under extremely slow speeds, the driver’s side motor would stall under low load. The motor and gearbox was removed for further inspection. Upon initial inspection the motor and gearbox were unable to be separated as the armature and motor housing were locked together as one. This caused the set screw in the gearbox mounting flange to not align with the access hole which disabled any attempt of removing the gearbox from the motor in a trouble-free manner. The gearbox had to be shimmed, and pryed (Figure 5.8) from the motor to allow further inspection to the motor to occur. No damage was caused during the disassembly process although a significant amount of force was used to separate the units.

Figure 5.8 -Separating Gearbox from Motor

When the motor was disassembled it could be seen that the armature was jammed against the permanent magnets of the motor housing because of a foreign object that wedged itself during rotation. The object had to be carefully removed with a pair of needle nose pliers to prevent further damage to the magnets or the armature. It was successfully removed and the damage minimized. The object was a small hardened steel rod (Figure 5.10) measuring 2 [mm] in diameter with the largest piece measuring 18 [mm] long. It appears that the loose material was present in the motor since delivery and could have been a part of the manufacturing process, as nothing resembled the material or shape at the shop. The damage to the armature can be seen in (Figure 5.10), the lamination was very slightly scored. The permanent magnets were cleaned up with emery clothed to remove any large burrs left from the scoring of the rod.

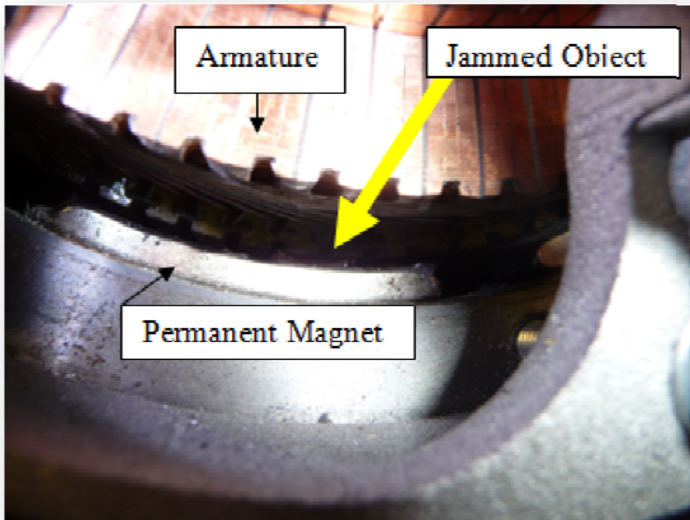


Figure 5.9 - Jammed Foreign Material Between Armature and PM

The motor was reassembled and tested on the bench, no interference was observed and the motor was deemed okay for reinstallation into the dune buggy. Further testing with the rebuilt motor was performed and no noticeable side effects could be seen from the slight damage that was present.

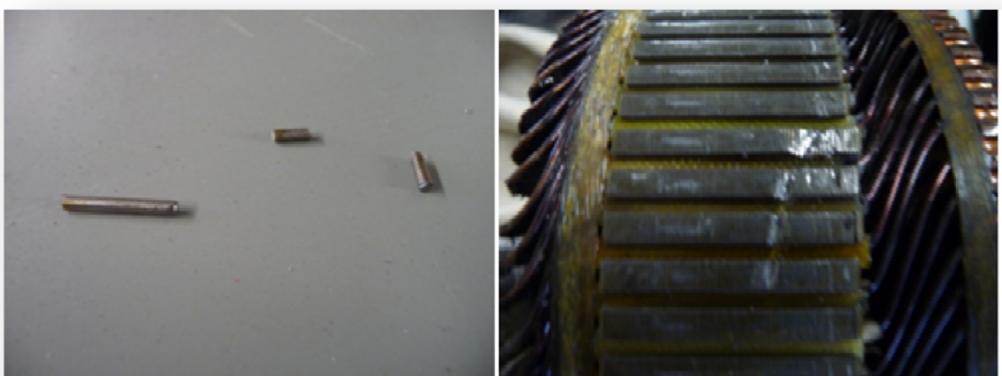


Figure 5.10 - Hardened Steel Rod and Damage to Armature

Chapter 6 Conclusions

The design process followed has brought many different innovative ideas to the table. By analysing the entire purpose and functionality of the problem a set of more accurate design parameters were formed with the customer's needs at the forefront. These design parameters were then subject to several prototypes which were evaluated and a simple yet very effective solution was found. The failure mode analysis that was performed pinpointed several possible failure modes that needed to be addressed for the next design iteration. These problems included reducing unsprung weight in the motor/gearbox housing assembly itself as well as reducing unsprung weight further in the actual design of the vehicle. Both objectives were completed in the final design. The existing hub assembly of the vehicle was removed (Figure 6.1b) and replaced with a similar version that adapts the gearbox mounting surface to the hub plate (Figure 6.1a). Then a rigidity study was done on the relationship of parameters found to be of importance in the FMEA study. These parameters were then studied later in the design cycle to determine which parameters should remained fixed and which can be variable to design to allow the most flexible design to emerge.

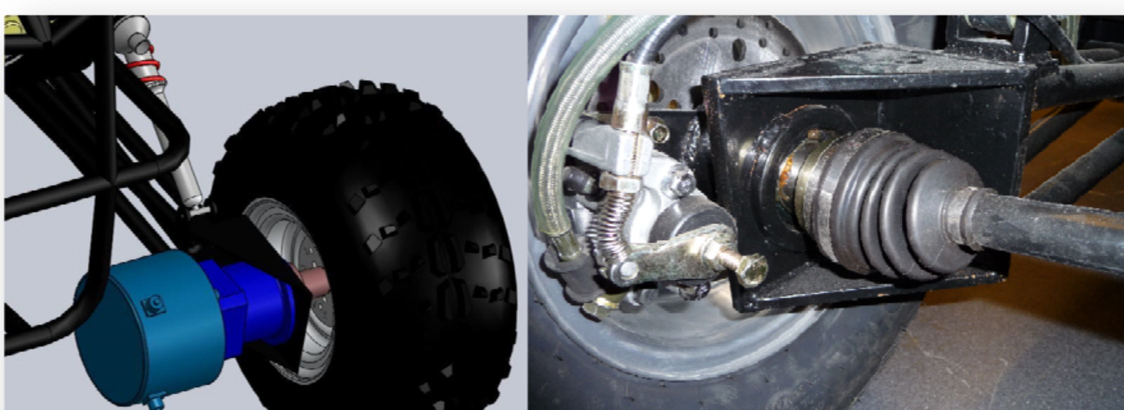


Figure 6.1 - Near Wheel Design(a) vs OEM Hub Assembly(b)

The Quality Function Deployment analysis that was performed allowed for a simple way of comparing the concepts to the design parameters found to be of utmost importance in the FMEA study and Rigidity analysis. The QFD analysis decided a clear winner in terms of design functionality in the parameters that were studied. Finally the entire design was subjected to the TRIZ 40 principles of design and 39 parameters of design for one final scrutiny on the decisions that were made.

The final outcome shown in Figure 6.1b shares considerable resemblance to the design found on the OEM dune buggy vehicle. This design cycle proves that a simple yet functional design is more effective then something that is more elaborate. Innovation does not necessarily mean for a design to become more complicated however more simplified.

The by-wire throttle is fully functioning and has removed all mechanical linkages associated with the OEM throttle, only wires connect the throttle to the controller. The device has shown its safety oriented ability to detect faults with a defective potentiometer, however has still allowed the vehicle to be driven with a quick reset.

The revolutionary by-wireless braking system has been proven to work in concept, and has been bench tested to show functionality of rear regenerative braking. The rear brake conversion from mechanically based hydraulic disc to 100% electric regenerative brakes is a success, however more real world testing/driving is needed in order to come to further conclusions and improvements to the system.

The overall efficiency gains by designing a near wheel motor can be seen by comparing Figure 3.1 the breakdown of the efficiencies of an ICE automobile and the improvements on these losses when compared to that of a near-wheel motor electric vehicle (Figure 6.2). It can be seen that all idling losses (17%) have been eliminated since electric motors draw no power while at idle. Drive train efficiencies have been increased from 82% efficient in transaxle/differential based automobiles to 96% total by using a only a direct drive planetary gearbox contributing to 6% of the total losses in an ICE automobile to a reduced 3% in the current prototype. Braking losses have been reduced slightly by capturing 10% of the losses with the rear regenerating by-wireless brakes. Lastly, all losses or inefficiencies (62%) associated with the gasoline engine have been eliminated with the all electric powertrain. Rolling resistance and aerodynamic drag remained unchanged due to no changes or improvements being made in those areas of study.

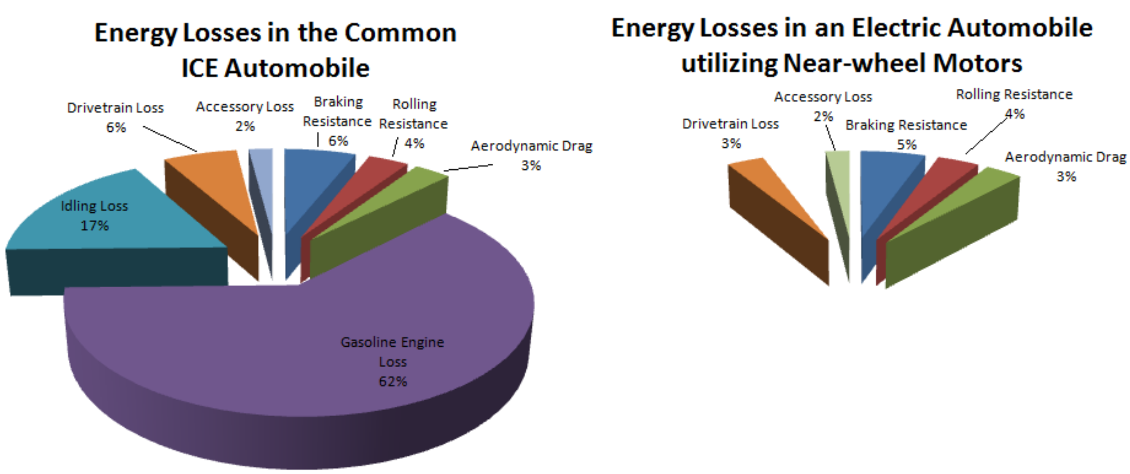


Figure 6.2 - Eliminated and Reduced Losses of Electric vs. ICE Automobile [43]

The final conclusions of this thesis are as follows:

- Vehicle has been converted to a 100% electric powertrain.
  - Resulting in a **78.7%** efficient powertrain (82% efficient motor coupled with 96% efficient planetary gearbox) compared to that of a combustion engine at 35-38% efficient coupled with an 82% efficient drivetrain for a total 31% efficiency. A **47.7%** improvement.

- Elimination of all idling losses of a common ICE automobile (17% of the total losses)

- Elimination of all inefficiencies associated with ICE losses (62% of the total losses, only 38% efficiency)

- A rear drive completely independent control architecture has been implemented.

- A rear drive near wheel motor solution has been designed and developed eliminating all mechanical transfer devices, including transmission, rear differential, and driveshafts.

    - Resulting in a 14% drivetrain efficiency gain (82% efficient transaxle/differential setup vs. 96% efficient direct drive planetary gearbox)

- Inboard space has been maximized with the advent of the powertrain being situated in the outer rear corners of the vehicle where common CV-shafts and rear differentials were situated.

- By-wire throttle through a potentiometer based gas pedal has been implemented and working effectively.

    - Complete removal of all mechanical linkages and cables for throttle input device.

- By-wireless rear regenerating brakes have been implemented and are currently in the testing phase.

    - Removal of rear hydraulic brakes, lines and hardware resulting in significant weight savings and reduction of brake fluid.

The efficiencies gained by the designs implemented in this thesis project have shown their ability to be used in a functioning motor vehicle. Direct gains in mechanical efficiency as well as the removal of a non eco-friendly gasoline powertrain have been attained. As well an electric architecture has been developed for further research in future studies such as vehicle stability control, traction control and all-wheel-drive architectures.

Chapter 7 Future work

The development of this vehicle will continue for years beyond the initial concept that has been created in this project. The foundation that has been created is a stepping stone in order to study emerging technologies such as hub motor drive train setups, series electric hybrid architectures and by-wire/wireless control systems.

The addition of motors to the front wheels of the vehicle will make the vehicle function with a truly independent, all wheel drive, setup. This setup will allow for traction control and stability control algorithms to be tested on a real world test vehicle which can allow for all wheels to act and respond independently, or in unison, from one another.

Further development is needed in the wireless communication protocol used in the braking, to allow for seamless uninterrupted communication between the transmitter and receiver. Wireless communications experts would need to be involved in order to determine the overall feasibility of incorporating this technology into a licensed motor vehicle. Developing a dependable power supply, finding fault-tolerant communication protocols (i.e., TTCAN and FlexRay™) and developing some level of hardware/mechanical redundancy would be the ultimate objective. Redundancy may also be incorporated into a proof of concept wireless system for purely experimental means with mechanical backup [47].

Many challenges exist in the further development of the hub motor architecture presented. By incorporating dense, permanent, magnet motors into the wheels of vehicles unsprung mass is increased. Design and development is needed in the housings for hub motors to be light weight, yet robust enough to survive in harsh automotive environments. Suspension designs can also combat the issue of unsprung mass, with the development of active suspension design utilizing magnet polymers to increase or decrease dampening as needed. Finally, motor development in the area of hub motors will need to be completed in order to reduce cost, maximize power and minimize weight.

The electronic differential needs to have feedback sensors installed onto the wheel assemblies to get the proper feedback on wheel speed. The current microcontroller works only a bench model and has not been implemented into the vehicle. Further work is needed in refining the speed measuring devices (reflective optic sensors) and coding the microcontroller for compensation.

Finally, the working concept as a whole has proven functionality as a motor vehicle with no major drawbacks to prevent it from being implemented into a passenger vehicle. It was the purpose of this thesis to create a test bed to prepare for the adaptation of the technology presented to be retrofitted into a Pontiac Solstice. Future work on developing synchronous systems with the existing can-bus architecture in the Solstice would need to be developed. In addition, a substantial increase in power would be needed to overcome the 1337 [kg] mass of the production vehicle. The increase in power would require motors with extremely dense power to volume ratios. A source for such motors would need to be found and developed concurrently with the systems of the vehicle. After the motor conversion has been completed existing monitoring devices such as wheel speed sensors would need to be adapted or disabled with the new systems being developed.

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Appendices

A. Prototype Build Pictures

Figure 7.1 - OEM Completely Stock Dune Buggy

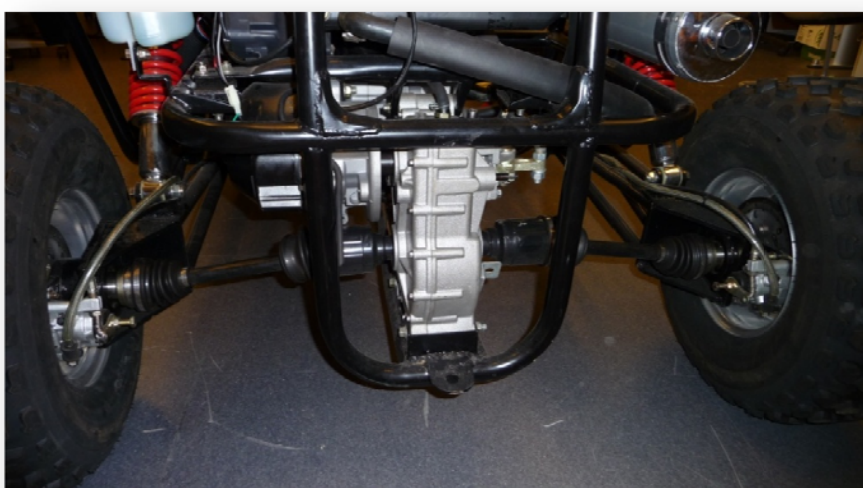


Figure 7.2 - OEM Drivetrain- Rear Differential, CV shafts, CVT Transmission

Figure 7.3 (a) - Dune Buggy at UOIT Design Exhibition

Figure 7.4 (b)- Dune Buggy at UOIT Design Exhibition

Figure 7.5 (c) - Dune Buggy at UOIT Design Exhibition

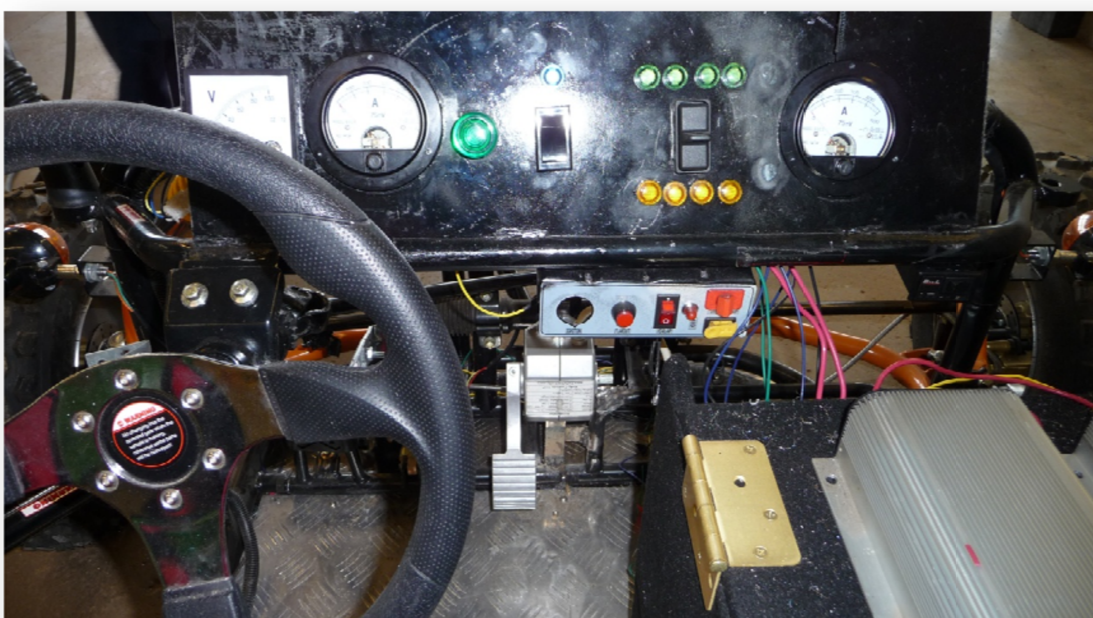


Figure 7.6 - Dash Board

B. Undergraduate Project Scope – First Design Iteration

ENGR 4220U Capstone

Project #7

Group #3

Group #3 (4 students): Joshi, Tarun, Mahavitane Sampath, Makki Noaman and Patel Vaibhav

"Client": Mark Bernacki andMatt Van Wieringen, MASc Students

Project Topic: Design and Development of an Innovative Plug-in Electric-ICE Dual Fuel By-Wire (wireless) Dune Buggy

Project Scope: Design, develop, build a physical prototype, test it, verify it and use it to demonstrate the functionality of the devised innovative **system/device(s)*.** Assume all necessary constrains as needed. The scope and emphasis should be in the area of modular design, designing component interfaces and modification, the design of the "packing" of components for the dune buggy and the design of its final assembly and disassembly.

Project Scope Detailed Outline

System/Devices* include:

Drive train:

Design and development of a mechanical solution to mount MOE708 – ETEK-R motor (ME0708_ETEK_R.pdf) with mated Neugart PLFE110-4 planetary gearbox (PLFE_110_gb.pdf) to form a rear wheel drive solution for the Baja style sand dune buggy.

The drive train solution should achieve the following:

Design and modification (if necessary) to existing dune buggy wheel bearing and hub assembly to permit fitment and mounting of the motor/gearbox assembly. Maintaining as much of the already manufactured dune buggy is preferred, as well as **utilizing existing components**. (wheel bearing/hub/suspension) The engineered solution will need to withstand significant vibration and shock due to the nature of the vehicle. (i.e. the motor and gear box **should not** be freely suspended on the inboard side, and **should** incorporate some sort of dampening system) This **robustness** should be **simulated** before a solution is implemented to ensure errors in the early design cycle are eliminated before prototype development occurs.

A solution to mount the output of the gearbox (flange) to the wheel will also need to be designed. The gearbox flange will need to be adapted to fit the stock wheels, or existing hub/lug plate.

This solution will simulate that of a **hub motor** design, the difference being that the motor/gearbox will not be housed within the wheel itself. Ultimately this means that the motor/gearbox/mating components will all be a part of the unsprung mass of the vehicle.

Assumptions:

The existing CVT transmission on the dune buggy can be assumed to be removed, as well as the rear differential and CV shafts.

Individual packaging and placement should also be engineered for the following components:

Steering**:

The steering wheel should be adapted to fit a potentiometer input device to monitor steering angle. Packaging of wiring should be considered in the placement of this device.

Brake/Accelerator**

Accelerator input device – gas pedal

Brake input device – brake pedal

Electrical components (passenger compartment)**:

Batteries

Micro controller

2 – Motor Controllers

Charger

DC/DC Converter

3 - Contactors

Main Disconnect

2 - Fuse Holder

Dashboard and Monitoring Visuals**

Display for Paktracker Battery monitoring

Wireless Key

Push Button – start

Shifter

Please see enclosed spreadsheet **Component Packaging_Location List.xls for details on above components.

The above is to be used as a guide line, it is open for modification as soon as the design process has been started. Please contact Matt or Mark frequently in the design cycle for clarification on any of the above to prevent errors in the later stages.

Deliverables: Provide all necessary engineering documentation for the system and related devices as per the generic marking rubric related to ENGR 4220U and ENGR 4221U.

C. Customer Feedback for Undergraduate Students

Group 3,

Very nice work on your concept generation stage! I have many concerns however. 1) A major problem with permanent magnet motors running on high currents 100A+ is that they generate huge amounts of heat. I am concerned that your housing will actually insulate this heat thus not allowing it to leave the motor.

Suggestion: Allow for an intake scoop and exhaust to your proposed housing, drawing air in from the front, and exiting out the back. Designed such that water/splashing etc are minimized.

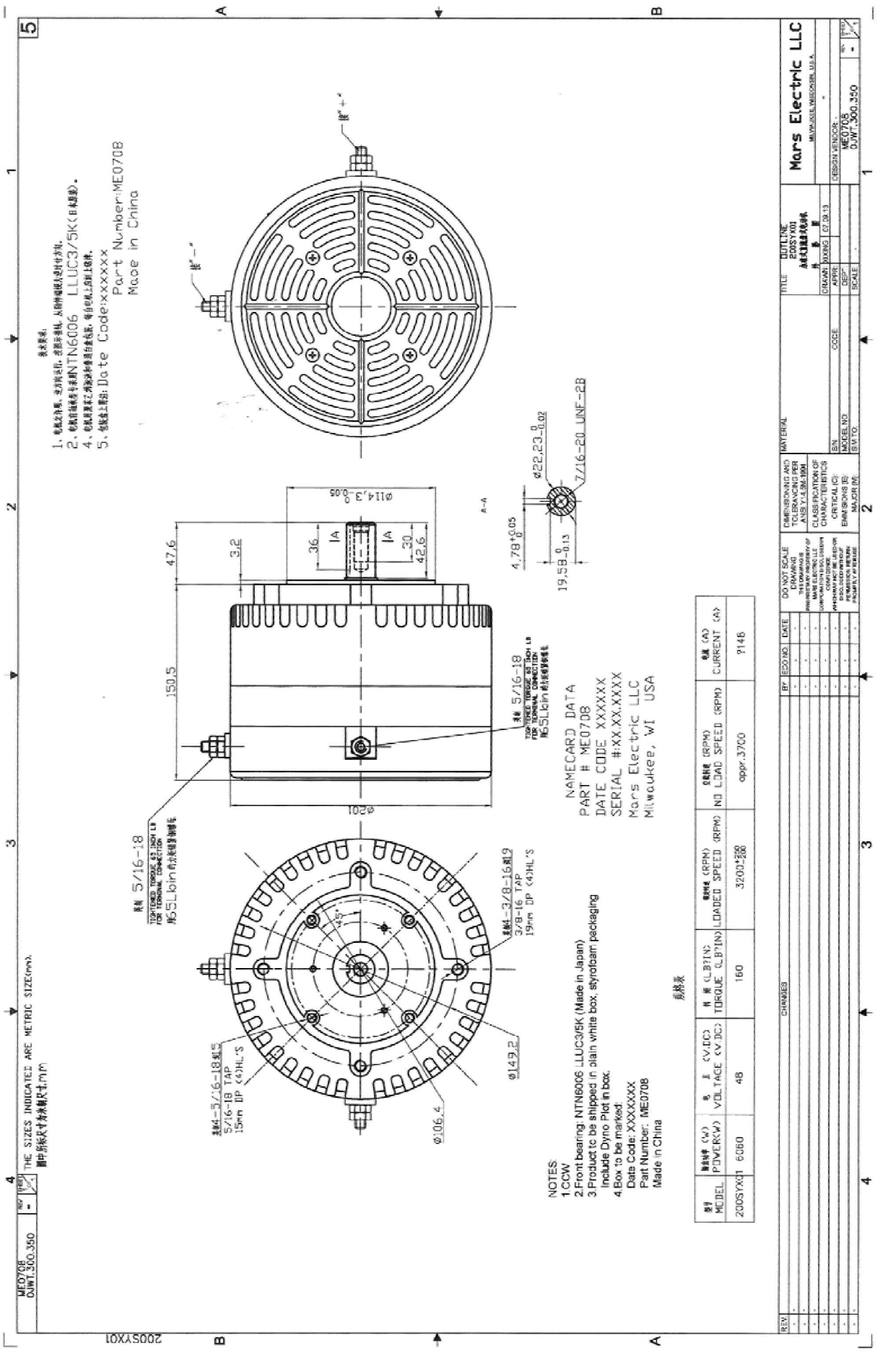
2) Manufacturability: Make sure whatever you design can be built... if you don't know how it would be built don't design it.... or figure out how it will be built.

3) As for the clutch, I have investigated various snap clutch solutions to the exact problem Dr. Remon mentions; however with the space constraints it is not a feasible solution. Alternative solutions will be very trivial - a) Very rough - motor to gearbox coupling is kept loose as to break free when excessive force is applied - i.e. stuck wheel under full throttle b) Slightly better - gearbox coupling has a shearable keyway, so when excessive force is applied key shears away and can be easily replaced.

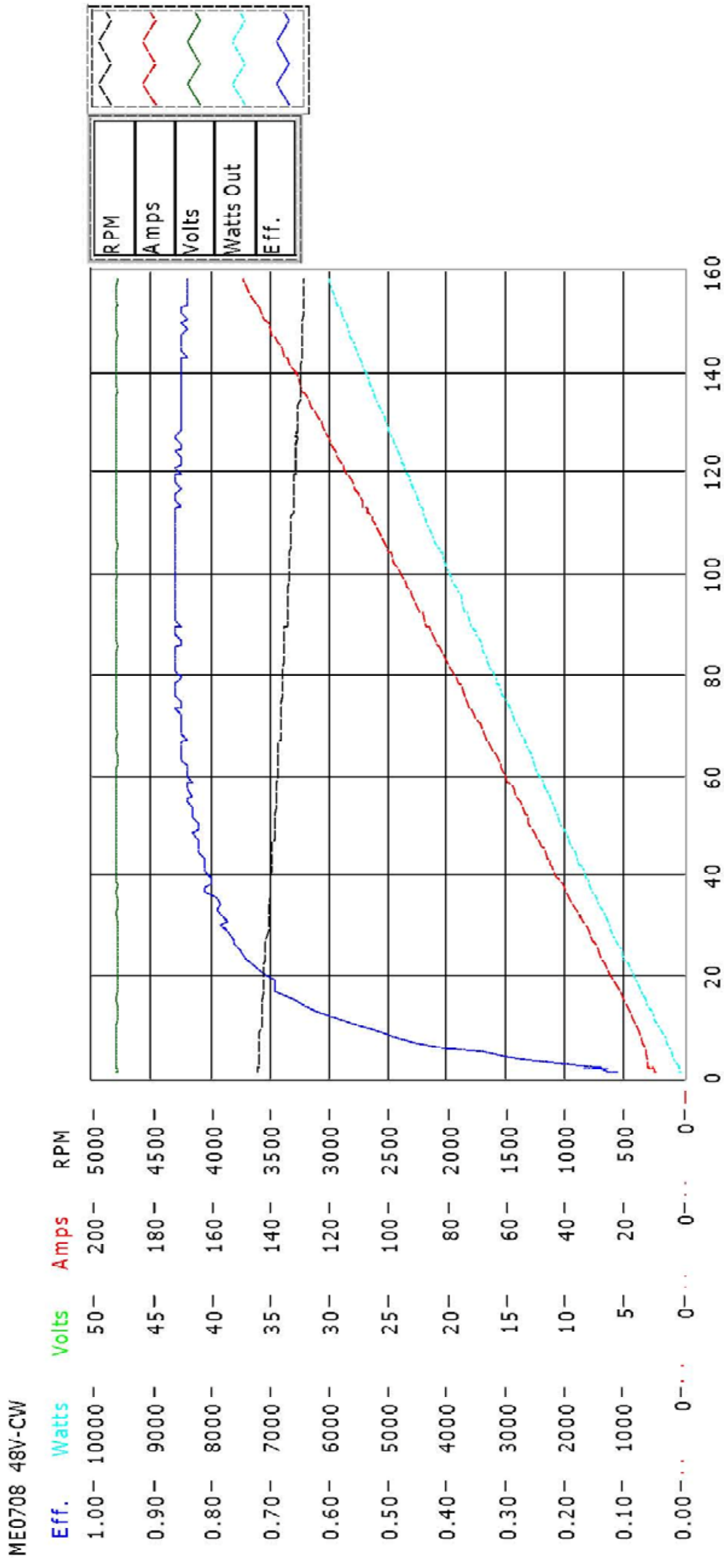
4) Suspension: The current suspension can be assumed NOT to work with the additional weight for multiple reasons 1) the additional weight of the batteries electronics for *sprung weight and 2) 10x+ the additional weight in unsprung weight (motor/gearbox. Having said this either secondary suspension to support the motor/gearbox weight will need to be added, or the spring/strut combo will need to be replaced with your design. Either way these components will need to be sourced and purchased.*

If you guys continue at this rate, this will be a very impressive presentation of your talents. Looking forward to seeing the final result!

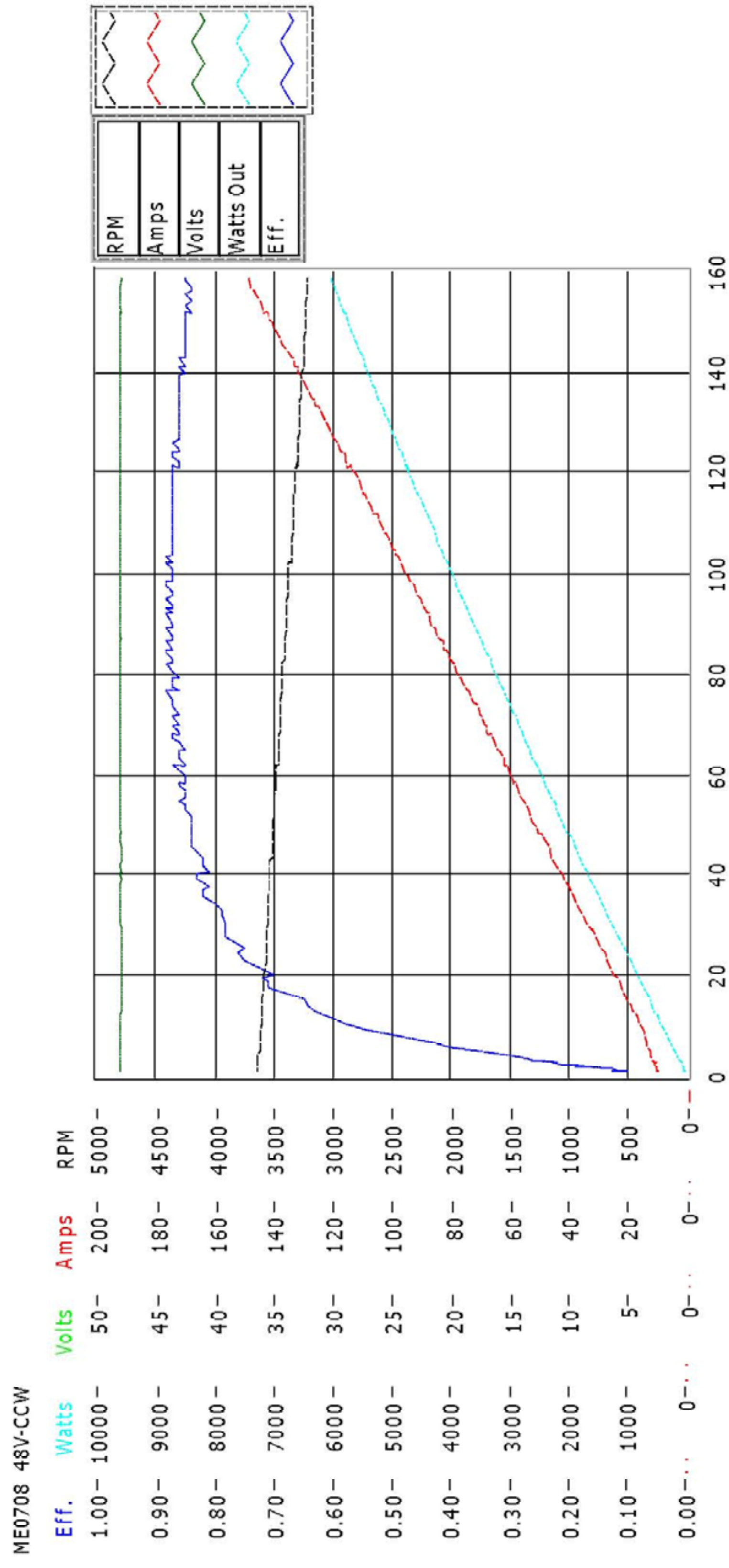
D. ETEK-R Motor Engineering Drawing



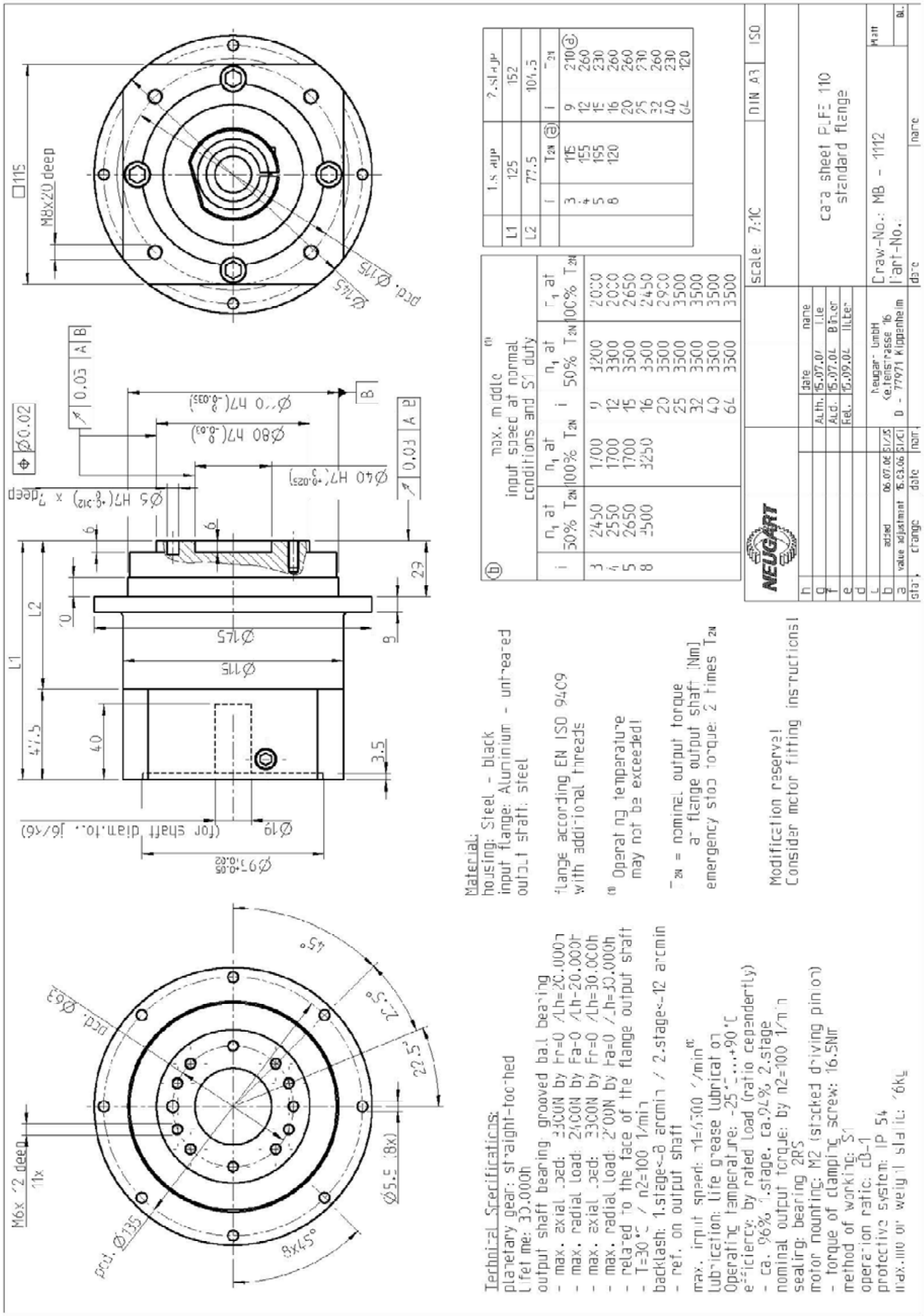
E. ETEK-R 48V Clockwise Dyno Graph



F. ETEK-R 48V Counter-Clockwise Dyno Graph



G. PLFE110 Planetary Gearbox Engineering Drawing



H. Kelly 72401 Controller Specifications

- SW2 can be configured as throttle switch.
- SW3 can be used as 5V supply of sensors.

2.4 Specifications

- Frequency of Operation: 16.6 KHz.
- Standby Current: less than 3 m A.
- Controller power supply current, PWR, 150mA.
- Controller power supply voltage, PWR, 18V to 90V.
- Minimum operating voltage, B+, 18V.
- Max regeneration voltage, B+, 1.25* Nominal.
- Throttle Input: 0-5 K, 5-0 K ohms, 0-5 Volts.
- Full Power Operating Temperature Range: 0C to 50 C (controller case temperature).
- Operating Temperature Range: -30C to 90 C, 100C shutdown (controller case temperature).
- Peak and Hold Main Contactor Driver: 3A peak, 1A hold.
- Alarm Output: 200mA.
- Armature Current Limit, 1 minute: 200A / 300A / 400A / 500A / 600A.
- Armature Current Limit, continuous: 80A / 120A / 160A / 200A / 240A.

2.5 Models

The naming regulations of the Kelly motor controller model:

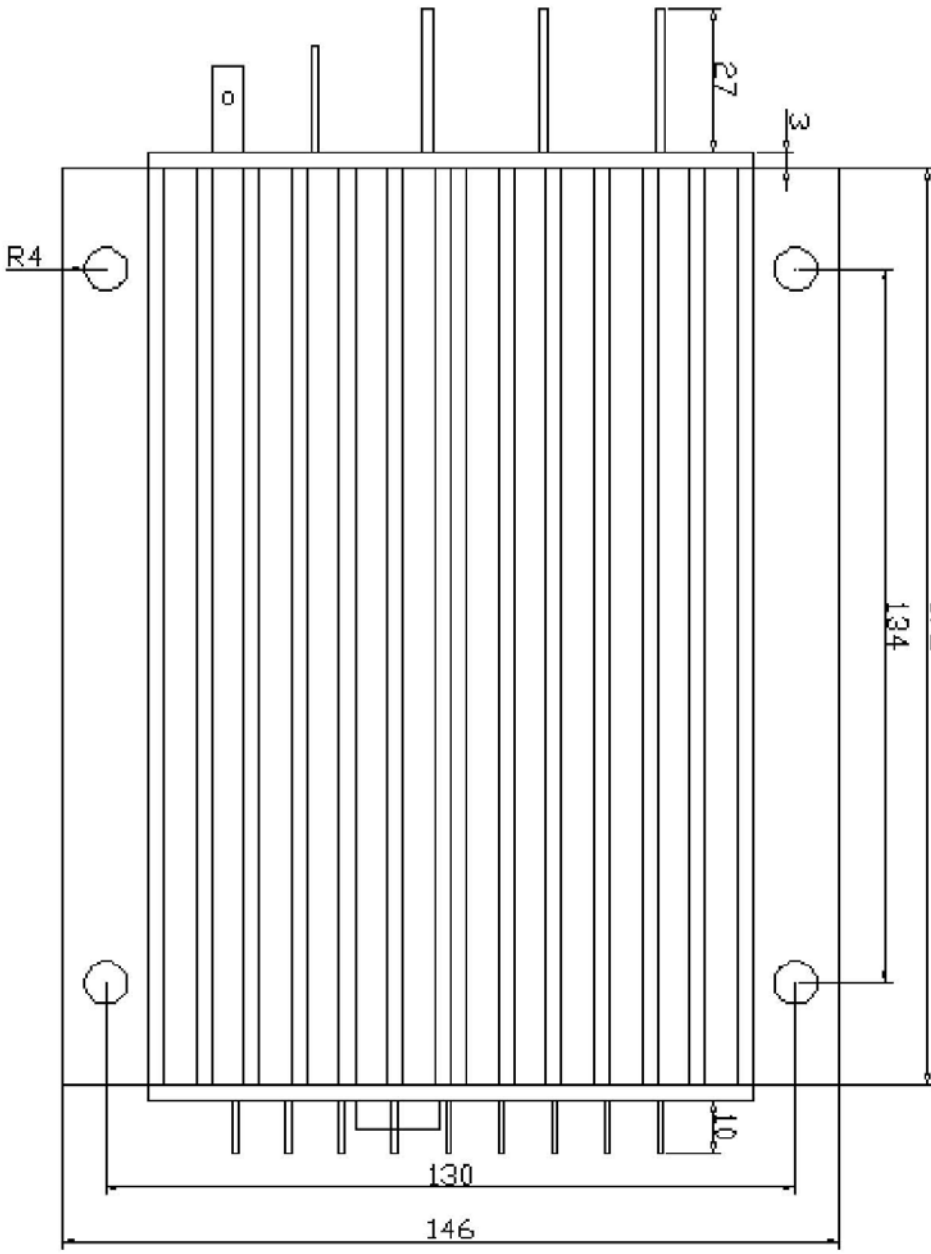
KD48301

The seventh letter represents regeneration (0:Series or PM Motor Controller; 1: PM Motor Controller with regeneration; 2 : Shunt Motor Controller; 3 : Shunt Motor Controller with regeneration).

The fifth and sixth letters represent the max current divided by 10.

The third and fourth letters represent the max rating voltage

The first and second letters represent Kelly's DC motor controller.



Tall: 62 millimeters

Figure 1: mounting holes' dimensions (dimensions in millimeters)

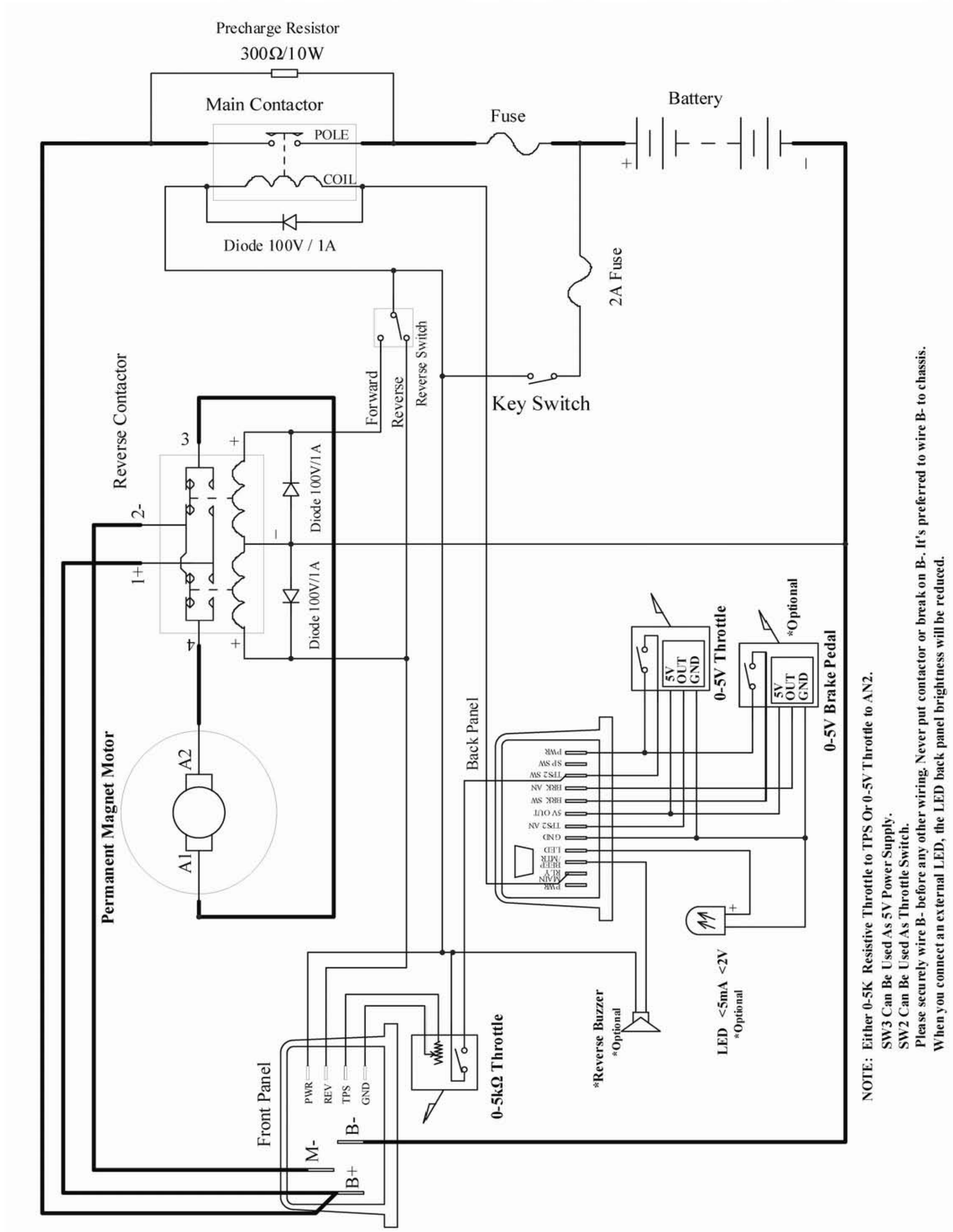


Figure 4: PM motor controller standard wiring

Chapter 2 Main Features and Specifications

2.1 General functions

(1) The controller measures battery voltage. It won't drive motor if B+ is higher than the maximum operating voltage. It also stops driving if battery voltage is too low. You can identify the error from LED codes. Under voltage threshold and over voltage threshold are configurable with PC GUI.

(2) The controller will close the main contactor after power on self-test. Then it waits a configurable time (default to 0.5s) for contactor bumping.

(3) Current loop and over current protection are built in for both field and armature. The field current is constant across all operation conditions except in the case of field weakening. Armature current is commanded by throttle position sensor.

(4) The armature current is trimmed down at low temperature and high temperature to protect battery and controller. The armature current will ramp down quickly over 90C. Both armature and field will shut down at 100C. Low temperature current ramping down usually starts at 0C.

(5) Cutting back current at low battery is built in every controller to extend battery life. ***Caution!*** *Excessive voltage drop on wiring may cause problem! Proper gauge of wire is required.*

(6) The max regeneration current is about half of max output current. ***Caution!*** *Regeneration can have braking effect, but it can't replace mechanical brake. The controller may shut down regen in some cases.*

(7) Max reverse speed is configurable to half of max forward speed.

2.2 Features

•Intelligence with powerful microprocessor,

• Synchronous rectification, fast PWM, and ultra low drop to provide high efficiency.

• Rugged aluminum housing for maximum heat dissipation.

•Current loop and over current protection for both field coil and armature.

•Current multiplication. Usually the armature current is much higher than the current drawn from battery.

•LED blinking code indicates fault sources.

•Battery protection: current cutback and turnoff when battery voltage is too low.

•Thermal protection: current cuts back at high temperature and low temperature to protect battery and controller.

• Critical parameters can be configured with GUI to best fit your application.

2.3 Optional Features (Terminals available on back side)

Following features are configurable through series communication with a host PC.

•"RLY" can be configured as a Peak and Hold Main Contactor coil driver.

•"PWM" is an output to drive Reverse Alarm.

• SW1 as Brake Switch is required for regeneration.

• 0-5V AN1 as Brake analog input can be configured for continuous variable regeneration.

• 0-5V AN2 can be configured as alternative throttle input.

I. TRIZ 39 Design Parameters

1) Weight of moving object

    Entire assembly would be moving while the vehicle is moving as well as when the suspension is moving. Unsprung weight is a critical parameter when designing a drivetrain which incorporates the hub. The unsprung mass is the mass of the suspension, wheels and other components directly connected to them, rather than supported by the suspension. The weight of assembly and all main components such as motor, gearbox and hub.
    Rotational mass is more critical, weight of rotational masses such as the weight of the spindle, and wheel/tire assembly.

2) Weight of nonmoving object

    All static masses, or sprung weight. Sprung mass (or sprung weight) is the portion of the vehicle's total mass that is supported above the suspension, including in most applications approximately half of the weight of the suspension itself, Masses which are part of the vehicles mass not including anything part of the suspension or wheel assemblies.

3) Length of moving object

    Overall length of motor/gearbox/hub assembly.

4) Length of nonmoving object

    Length of all supporting components not a part of the actual drivetrain.

5) Area of moving object

    Overall area or foot print of motor/gearbox/hub assembly.

6) Area of nonmoving object

    Area or foot print of all supporting components not a part of the actual drivetrain or unsprung mass.

7) Volume of moving object

    Overall volume of motor/gearbox/hub assembly. The critical space that the assembly occupies in the vehicle.

8) Volume of nonmoving object

    Volume of all supporting components not a part of the actual drivetrain or unsprung mass. The critical space that the assembly occupies in the vehicle.

9) Speed

The speed that the motor/gearbox will need to reach in order to make the vehicle reach desired speeds.

10) Force

The amount of force the motor/gearbox will need to produce in order to move the vehicle at the desired speed/acceleration.

11) Tension, pressure

Various stress points in design of motor/gearbox assembly. How force and speed will be dealt with in design and in preliminary FMEA, and FEA.

12) Shape

The form the design will take, including housing, motor, gearbox.

13) Stability of object

During operation will the housing be substantial enough to maintain the stability of the system.

14) Strength

Determined in FEA analysis, and proven during prototype testing.

15) Durability of moving object

All moving aspects of the design will need to be durable enough to withstand normal and excessive driving habbits.

16) Durability of nonmoving object

All nonmoving aspects of the design will need to be durable enough to withstand normal and excessive driving habbits.

17) Temperature

Temperatures include cold weather testing -30*C to hot climate testing 100+*C

18) Brightness – NA

19) Energy spent by moving object

A critical factor in the design of an electric vehicle, motor and gearbox have to be designed to meet the needs of the vehicle, and to choose an energy storage device equivalent for the needs of the vehicle.

20) Energy spent by nonmoving object

All sprung mass will need to be transported which will attribute to a larger overall vehicle mass, this will need to be minimized as the more overall vehicle mass the more energy that will be needed in order to propel it.

21) Power

The power of the system will need to be coupled with the desired top speed and acceleration of the system.

22) Waste of energy

Waste energy in terms of braking will need to be address (regen braking) as well as waste heat energy from the electric motors.

23) Waste of substance

None

24) Loss of information

None

25) Waste of time

Repair ability, the ability to assemble and disassemble.

26) Amount of substance

NA

27) Reliability

The entire system should perform to its desired intention and during irregularities in the driving cycle should continue to perform without incident.

28) Accuracy of measurement

Accuracy in measuring overall vehicle weight and desired power outputs is critical in the overall performance of the vehicle.

29) Accuracy of manufacturing

With many parts being machined to strict tolerance levels, this accuracy is critical in order for part fitment and functionality.

30) Harmful factors acting on object

Factors such as weather, cooling, chemicals (gasoline, hydrogen, hydraulic fluid)

31) Harmful side effects

Lack of robustness of the system could lead to system failure which could result in loss of control of the vehicle and operator injury.

32) Manufacturability

All components would need to have a means of a manufacturability and assembly, including motor/gearbox assembly as well as housings and associated components.

33) Convenience of use

The design should be implemented such that hub/motor/gearbox assemblies are seamless to the operator.

34) Reparability

All components should be designed in such a fashion that repairs if needed can be performed with relative ease. Access of the motor and gearbox are essential for this to occur.

35) Adaptability

Design should be easily implemented in other vehicle architectures in order to display the technology in multiple forums.

36) Complexity of device

The devices complexity should be minimized in terms of manufacturability, use and installation.

37) Complexity of control

Control systems for electronic components are inherently more complex then mechanically drive systems, thus electronic controls should remain simple to the operator although the depth of the actual controls maybe quite complex.

38) Level of automation

Level of automation in an electric drivetrain will be high, all drive train components should be self automated with overall control being offered to the operator.

39) Productivity

The system should produce the desired outputs of moving the vehicle as desired by the operator.

J. Triz 40 Inventive Parameters Analyzed

Principle 1. Segmentation

A. Divide an object into independent parts.

o *The concept and use of independent unit operations in the development of a hub motor system*

o *The use of different components of a unit operation to allow the vehicle to be propelled at the desired rate of speed according to the operator*

o *Separate components that interact with each other include, gearbox, motor, motor/gearbox housing, motor controllers, contactors, relays, power supply etc.*

o *Separate pipeline of energy transport, wires, fuses, junction blocks.*

B. Make an object easy to disassemble.

o *Bolts, screws, brackets instead of welds.*

o *Easily accessible to perform disassembly.*

C. Allow components to be interchanged, upgraded or enhanced .

- *Universal brackets for mounting to hub*
- *Gearbox to motor coupling allowing for modification for modular shafts*
- *Motor gear box housing allowing for exchange of gearbox and motor.*
-

Principle 2. Taking out

A. Separate an interfering part or property from an object, or single out the only necessary part (or property) of an object.

- *Remove gearbox from motor to see how motor performs.*
- *Utilize only 1 motor and controller to see effects of draw on batteries utilizing appropriate detection gauges.*
- *Utilize multiple heat/vibration sensors to distinguish bearing failure, gear box failure or motor failure*

Principle 3. Local quality

A. Change an object's structure from uniform to non-uniform, change an external environment (or external influence) from uniform to non-uniform.

- *Use water proof / weather proof motor and gearbox assemblies, which would not require a housing cover*
- *Use non-corrosive materials such as aluminum which also reduce weight or zinc plated steel*
- *Use beam related structures instead of solid walls, adding additional venting/cooling*

B. Make each part of an object function in conditions most suitable for its operation.

- *Motor should spin at most efficient RPM*
- *Gearbox should adjust motors max efficiency RPM with vehicles suited RPM*

C. Make each part of an object fulfill a different and useful function.

- *Motors should be used as power delivery devices and used as generators while in braking (regenerative braking)*
- *Independent drive train should also be utilized as independent traction devices detecting slippage and controlling overall vehicle handling.*

Principle 4. Asymmetry

A. A. Change the shape of an object from symmetrical to asymmetrical.

- *Asymmetrical gearbox/motor housing*
- *Asymmetrical wire feeding (left and right motors) to minimize the amount of heavy gauge wire used.*

B. If an object is asymmetrical, increase its degree of asymmetry.

- *Assymetrical motor/gearbox housing can be reduced in weight with a higher degree of asymemetry, reducing material where it is not needed.*

Principle 5. Merging

A. Bring closer together (or merge) identical or similar objects, assemble identical or similar parts to perform parallel operations.

- *Battery box to also store electronics – motor controllers, fuses, contactors, microcontroller*
- *Multiple motor controllers substituted with single controllers with multiple outputs.*

B. Make operations contiguous or parallel; bring them together in time.

- *Motor speeds should be compared through microcontroller, adding encoders to detect wheel speed.*
- *Battery state of charge and possible power output should be communicated and limited.*

Principle 6. Universality

A. Make a part or object perform multiple functions; eliminate the need for other parts.

- *Utilize a geared motor to eliminate the need for a separate gearbox and associated housing*
- *Utilize a high torque, low rpm electric motor which will allow the total elimination of a gearbox*
- *Utilize true hub-motor's in order to utilize the wheel itself as a housing for the motor/gearbox assembly.*

Principle 7. "Nested doll"

A. Place one object inside another; place each object, in turn, inside the other.

- *Motor + Gearbox + housing could all be nested inside the wheel/rim making it a true hub motor setup.*

B. Make one part pass through a cavity in the other.

NA

Principle 8. Anti-weight

A. To compensate for the weight of an object, merge it with other objects that provide lift.

- Merge hub-motor assembly, gearbox, motor with existing suspension to add dampening to the entire system and control.

B. To compensate for the weight of an object, make it interact with the environment

(e.g. use aerodynamic, hydrodynamic, buoyancy and other forces).

- *Allow wind deflectors at bottom of motor/gearbox housing to aid in cooling and giving aerodynamic lift, thus supporting the weight of the hub-motor structure.*

Principle 9. Preliminary anti-action

A. If it will be necessary to do an action with both harmful and useful effects, this action should be replaced with anti-actions to control harmful effects.

- *Adding mass to the unsprung mass of the vehicle will attribute to negative handling characteristics. These characteristics should be combated with other technologies such as adjustable suspension, active dampening suspension (eletro-magnetic) or secondary suspension systems.*
- *Adding a gearbox to the electric motor creates losses, a motor with slightly higher power output should be chosen to overcome these losses.*

B. Create beforehand stresses in an object that will oppose known undesirable working stresses later on.

- *FEA analysis will be performed on all manufactured parts.*
- *FMEA will also be performed to identify and correct possible failures due to stress.*

Principle 10. Preliminary action

A. Perform, before it is needed, the required change of an object (either fully or partially).

- *Motors will come with appropriate terminals for wiring*
- *Gearboxes will come with appropriate couplers for associated motor*

B. Pre-arrange objects such that they can come into action from the most convenient

place and without losing time for their delivery.

- *NA – Early prototyping stage*

Principle 11. Beforehand cushioning

A. Prepare emergency means beforehand to compensate for the relatively low reliability of an object.

- *Extra key, for keyway on motor to gearbox, and gearbox to hub*
- *Ability to run vehicle with only 1 motor, if second motor fails*
- *FMEA analysis will cover more in depth failure modes*

Principle 12. Equipotentiality

A. In a potential field, limit position changes (e.g. change operating conditions to eliminate the need to raise or lower objects in a gravity field).

- *Limit suspension travel on rear wheels to reduce movement of unsprung weight.*

Principle 13. 'The other way round'

A. Invert the action(s) used to solve the problem (e.g. instead of cooling an object, heat it)

- *Instead of removing differential and adding two motors, add a differential and continue to use one motor, which is electric.*

B. Make movable parts (or the external environment) fixed, and fixed parts movable).

- *Do not allow motors/gearboxes on rear wheels to move with suspension, fix suspension.*
- *Motor controllers and electronic devices currently mounted in a fixed location can be mounted in such a fashion such that their location could be changed to suit the operator.*

C. Turn the object (or process) 'upside down'

- *Invert motor/gearbox housing 180* from current position*

Principle 14. Spheroidality - Curvature

A. Instead of using rectilinear parts, surfaces, or forms, use curvilinear ones; move

from flat surfaces to spherical ones; from parts shaped as a cube (parallelepiped) to ball-shaped structures.

- *Remove beam like architecture from motor housing and utilize rods*
- *Remove all flat surfaces encompassing a rectilinear shape in motor/gearbox housing and chamfer, filet and round all edges. Reducing mass and allowing better airflow.*

B. Use rollers, balls, spirals, domes.

- *Add spherical joint from motor/gearbox to hub (i.e. CV joint)*

C. Go from linear to rotary motion, use centrifugal forces.

- *Spherical motion currently being utilized in motor/gearbox/hub.*

Principle 15. Dynamics

A. Allow (or design) the characteristics of an object, external environment, or process to change to be optimal or to find an optimal operating condition.

- *Process control based on variable input as to optimum set points*
- V*ariable speed motor*
- *Adjustable settings on voltage to motor for top speed*

B. Divide an object into parts capable of movement relative to each other.

- *Motor output shaft*
- *Gearbox, input coupler and output shaft*
- *Hub bearing shaft*
- *Hub mounting*

C. If an object (or process) is rigid or inflexible, make it movable or adaptive.

- *Adding CV shaft to allow motor/gearbox to flex from hub mount*

Principle 16. Partial or excessive actions

A. If 100 percent of an object is hard to achieve using a given solution method then,

by using 'slightly less' or 'slightly more' of the same method, the problem may be considerably easier to solve.

- *Add motor which may be considered overpowered for application*
- *Add additional voltage, or energy storage capacity for speed and distance*
- *Gearbox to have higher gear ratio then intended to compensate for abnormal frictional stresses.*

Principle 17. Another dimension

A. To move an object in two- or three-dimensional space.

- *Add joystick for control which can be moved in 3 separate axis for directional control, braking and throttle.*

B. Use a multi-story arrangement of objects instead of a single-story arrangement.

- *Motor controllers and electronics mounted on both sides of the mounting surface*

C. Tilt or re-orient the object, lay it on its side.

- *Move motors to an upright position, allowing for vertical space to be consumed by utilizing a beveled gears within the gearbox.*

D. Use 'another side' of a given area.

- *Stack motor controllers, fuses, contactors instead of spreading them on a flat mounting surface*

Principle 18. Mechanical vibration

A. Cause an object to oscillate or vibrate.

- *Want to avoid vibration by balancing entire rotational system, motor, gearbox, wheel.*

B. Increase its frequency (even up to the ultrasonic).

- *Possible motor controller frequency adjustment (i.e. PWM)*

C. Use an object's resonant frequency.
- *NA*

D. Use piezoelectric vibrators instead of mechanical ones.
- *NA*

E. Use combined ultrasonic and electromagnetic field oscillations.
- *NA*

Principle 19. Periodic action

A. Instead of continuous action, use periodic or pulsating actions.
- *PWM DC Voltage control instead of resistor based variable voltage*

B. If an action is already periodic, change the periodic magnitude or frequency.
- *Alternate the cycle of PWM control*

C. Use pauses between impulses to perform a different action.
- *Pause the cycle of PWM control or voltage supply when coasting*

Principle 20. Continuity of useful action

A. Carry on work continuously; make all parts of an object work at full load, all the time.
- *While braking allow motors to give resistance and restore energy (regenerative braking)*
- *Have electric motors attached to flywheel, and clutch to keep movement continuous.*

B. Eliminate all idle or intermittent actions or work.
- *Allow charging to batteries and draw to occur at the same time through a generator*

Principle 21. Skipping

A. Conduct a process, or certain stages (e.g. destructible, harmful or hazardous operations) at high speed.
- *NA*

Principle 22. "Blessing in disguise" or "Turn Lemons into Lemonade"

A. Use harmful factors (particularly, harmful effects of the environment or surroundings) to achieve a positive effect.
- *Capture wasted heat from braking and convert to energy to recharge batteries*
- *Utilize motors for regenerative braking.*

B. Eliminate the primary harmful action by adding it to another harmful action to resolve the problem.
-

Principle 23. Feedback

A. Introduce feedback (referring back, cross-checking) to improve a process or action.

- *Add encoder feedback from wheels to motor controllers for more advanced control in traction aiding systems, stability systems and performance.*
- *Heat sensors to control motor temperatures*
- *Ammeter, voltage, temperature probes for batteries to monitor and maintain state of charge.*

B. If feedback is already used, change its magnitude or influence.

- *Change armature feedback to encoder feedback.*

Principle 24. 'Intermediary'

A. Use an intermediary carrier article or intermediary process.

- *NA*

B. Merge one object temporarily with another (which can be easily removed).

- *NA*

Principle 25. Self-service

A. Make an object serve itself by performing auxiliary helpful functions

- *Utilize motors for regenerative braking.*

B. Use waste resources, energy, or substances.

- *Utilize motors for regenerative braking.*

Principle 26. Copying

A. Instead of an unavailable, expensive, fragile object, use simpler and inexpensive copies

- *All fuse holders, contactors generic easily replaceable*
- *Wire terminals and lugs, universal and easily sourced.*
-

B. Replace an object, or process with optical copies

- *NA*

C. If visible optical copies are already used, move to infrared or ultraviolet copies

- *NA*

Principle 27. Cheap short-living objects

A. Replace an inexpensive object with a multiple of inexpensive objects, comprising certain qualities (such as service life, for instance)

- *NA – all objects are permanent with long life cycles.*

Principle 28 Mechanics substitution

A. Replace a mechanical means with a sensory (optical, acoustic, taste or smell) means

- *Replace keyway which is the weak link with an electronic or electromagnetic clutch.*

B. Use electric, magnetic and electromagnetic fields to interact with the object

- *Utilizing permanent magnet motors (also see 28-A)*

C. Change from static to movable fields, from unstructured fields to those having structure

- *NA*

D. Use fields in conjunction with field-activated (e.g. ferromagnetic) particles

- *NA*

Principle 29. Pneumatics and hydraulics

A. Use gas and liquid parts of an object instead of solid parts (e.g. inflatable, filled with liquids, air cushion, hydrostatic, hydro-reactive).

- *Pneumatic clutch instead of plate clutch.*

Principle 30. Flexible shells and thin films

A. Use flexible shells and thin films instead of three dimensional structures

- *Flexible fuel storage tank*

B. Isolate the object from the external environment using flexible shells and thin films.

- *Isolate battery storage with outer-shell, for both operator safety and battery protection.*

Principle 31. Porous materials

A. Make an object porous or add porous elements (inserts, coatings, etc.)

- *Drill holes in the motor/gearbox housing to reduce the weight*

B. If an object is already porous, use the pores to introduce a useful substance or function.

- *Pores in motor/gearbox housing can be used to extract heat and induct cooling*

Principle 32. Color changes

A. Change the color of an object or its external environment.

- *All wires colour coded to describe, power, ground, accessory wires*

B. Change the transparency of an object or its external environment.

- *Place transparent cover over top of electronics, for both asthetics and for viewing fuses, and connections for maintenance purposes.*

Principle 33. Homogeneity

A. Make objects interacting with a given object of the same material (or material with identical properties).

- *All manufactured brackets, housings, devices will be made out of aluminum due to its weight to strength characteristics as well as its ability to be manufactured/machined with relative ease.*

Principle 34. Discarding and recovering

A. Make portions of an object that have fulfilled their functions go away (discard by

dissolving, evaporating, etc.) or modify these directly during operation.

- *NA – not a disposable design*

B. Conversely, restore consumable parts of an object directly in operation.

- *Regenerative brushes on a permanent magnet motor?*

Principle 35. Parameter changes

A. A. Change an object's physical state (e.g. to a gas, liquid, or solid)

- *Possible different states of batteries design*

B. Change the concentration or consistency.

- *NA*

C. Change the degree of flexibility.

- *Use motors which allow for a higher voltage then needed to increase max speed if needed by adding additional voltage*

D. Change the temperature.

- *Optimize motors operation temperature*

Principle 36. Phase transitions

A. Use phenomena occurring during phase transitions (e.g. volume changes, loss or

absorption of heat, etc.).

- *NA*

Principle 37. Thermal expansion

A. Use thermal expansion (or contraction) of materials.

- *Fit motor, gearbox, hub with possible heating/cooling methods for interference fit*

B. If thermal expansion is being used, use multiple materials with different coefficients of thermal expansion.

- *Contradicts 33A*

Principle 38. Strong oxidants

A. Replace common air with oxygen-enriched air

- *NA*

B. Replace enriched air with pure oxygen

- *NA*

C. Use ionized oxygen.

- *NA*

D. Replace ozonized (or ionized) oxygen with ozone.

- *NA*

Principle 39. Inert atmosphere

A. Replace a normal environment with an inert one

- *NA*

B. Add neutral parts, or inert additives to an object

- *NA*

Principle 40. Composite materials

A. Change from uniform to composite (multiple) materials

- *Composite material can be used for the battery box, and motor/gearbox housing and cover.*